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Weather forecasting as a problem in fluid dynamics*

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Summary

Recent advances in the use of physico-mathematical models to forecast the weather over the northern hemisphere for up to six days ahead are described. A higher-resolution model is used to predict the evolution of smaller-scale weather systems such as fronts and their associated rainfall over western Europe up to 36 hours ahead. An example of a five-day numerical forecast and its verification is presented.

The concepts of precision, accuracy, assessment and evaluation of forecasts are discussed together with the factors that ultimately limit their accuracy and range. The improvement in both surface and upper-air forecasts since the introduction of computer models is demonstrated by both objective tests and more subjective judgements.

1. Introduction

During the last decade the traditional, empirical and largely subjective methods of weather forecasting that depend heavily on the experience, skill and judgement of the individual human forecaster have gradually given way to objective mathematical predictions made with the help of powerful electronic digital computers. The whole operation, described in some detail by Mason (1973), consists of three stages: data acquisition and processing, analysis, and prediction, and consists basically of forming a three-dimensional representation of the conditions prevailing through a large volume of the atmosphere at a particular moment of time, and of predicting, from an observed initial state, the future evolution and movement of atmospheric disturbances and their associated weather. Using standardized observations and measurements, made simultaneously at fixed times over a large part of a continent or even a hemisphere, and exchanged rapidly between different countries in universally agreed codes over a special global network of satellite, cable, radio- and picture-transmission channels, charts are constructed to depict the current distribution of atmospheric pressure, temperature, humidity, winds, etc. at the earth's surface and at a number of levels in the upper air, and from these are evolved forecast charts showing the conditions expected some hours or days later.

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2. Description of weather prediction models

The numerical predictions are objective, mathematical exercises based on a firm structure of physical theory that treats the atmosphere as a vast, turbulent, rotating fluid with energy sources and sinks. They involve the construction of physico-mathematical models which, although necessarily simplified compared with the complexity of the real atmosphere, must nevertheless adequately represent the physical and dynamical processes that are likely to control developments on the space and time scales of interest. In other words, the models must properly represent the relevant or significant scales of motion and their non-linear interactions, but smooth out all the smaller-scale motions that cannot be adequately observed or represented individually while allowing for their overall contribution to transport and energy-conversion processes by representing their statistically averaged properties in terms of larger-scale parameters that can be measured. The theory is based on the physical principles of conservation of momentum, mass, energy and water substance, the Newtonian (Navier–Stokes) equations of motions applied to a parcel of air, the laws of thermodynamics, and the equation of state of a gas.

If we consider, at first, a dry atmosphere containing no water substance, the full set of governing equations is as follows:

Equations (1) and (2). Two equations describing the horizontal motions of the air in which the time rates of change of the E–W and N–S components of the wind are related to the forces exerted on the air by the rotation of the earth, by horizontal pressure gradients, and by retarding forces such as friction and turbulence.

Equation (3). A similar equation describing the vertical motion of the air under the influence of forces that arise from gravity, vertical pressure gradients, rotation of the earth, and from frictional and turbulent stresses.

Equation (4). An equation of continuity which relates changes in the density and velocity of the air in such a way that mass is everywhere conserved.

Equation (5). A thermodynamic equation which relates the supply of heat to a parcel of air to the resultant changes of temperature and pressure.

Equation (6). An equation of state connecting the pressure, density and temperature of the air.

This set of six equations, which may be found in Mason (1971), involves six dependent variables: the three components of the wind, and the pressure, density and temperature of the air, all expressed as functions of space and time. In order to include the effects of evaporation, condensation and precipitation of moisture, equations are added for the continuity of the water substance and the heating term is modified to include the release of latent heat.

Starting from a given initial situation and specified boundary conditions, the problem is to solve a system of simultaneous non-linear partial differential equations in three spatial dimensions with time as the fourth independent variable. In fact, the equations are formulated in such a manner that they allow the time variations of the above quantities to be determined from their spatial variations. Thus, in principle, if we can observe the initial values of all the variables at a network of discrete points filling the whole or a large part of the atmosphere, we can compute the initial time rate of change of each variable from the governing equations, and then extrapolate over a short time interval to find a *predicted value* at each point in the network. Repeating this process step by step, we can build up a forecast of the fields of pressure, wind, temperature, humidity, etc.

In practice, the meteorologist measures the horizontal winds (by tracking balloons with radar), and the atmospheric pressure, temperature and humidity, but not the vertical component of the air motion since this is usually too small to measure directly although of the greatest importance in controlling cloud- and rain-forming processes. In order to get over this difficulty and, at the same time, eliminate

the density of the air as a variable from the equations, we use pressure rather than height as the vertical co-ordinate, regarding this as an independent variable and introduce, as a dependent variable, the contour height, which is the height of a constant pressure (isobaric) surface. Maps of contour heights are very similar, in configuration and in their relation to the winds, to those of the corresponding pressure fields. The thermal structure of the atmosphere is described in terms of the thickness of the layers between isobaric surfaces, the thickness being proportional to the average temperature of the layer. In this system, the vertical velocity of the air is represented by the time rate of change of atmospheric pressure, and is defined entirely by the horizontal wind field. Further simplification is introduced by rewriting the thermodynamic equation in a form that relates the vertical motion to changes in the non-adiabatic heating and the thickness of the layer, so that the dependent variables become the two horizontal components of the wind, the time rate of change of the atmospheric pressure (closely related to the vertical motion), the contour height, thickness, and humidity of the layers between isobaric surfaces, and the precipitated water (rain and snow).

Such complex physico-mathematical models have been developed in the Meteorological Office and described by Burridge and Gadd (1977) to replace a simpler model which formed the basis of its daily forecasting operations between 1965 and 1972.

The current model is designed to simulate and predict the evolution of major weather systems over practically the whole of the northern hemisphere for several days ahead. The basic governing equations are essentially those described earlier and include those for the continuity of moisture. If a layer of air is unsaturated, the humidity is allowed to change by horizontal and vertical air motions and by evaporation of rain or snow falling into it from above. Once a layer reaches saturation, its excess moisture is deemed to condense and fall out as rain or snow (depending upon the temperature) into the layer below. The latent heat released or absorbed during the processes of condensation, evaporation, freezing and melting, is calculated and its dynamical consequences computed. The model allows for modification of the airflow by the underlying topography, for the frictional drag of the land and sea on the air and for horizontal eddy diffusion. Adjustments are also made to allow for the vertical transport of heat and moisture by both shallow and deep convective clouds that are smaller than the computational grid. In computing the exchanges of sensible and latent heat at the earth's surface, the surface albedo is specified at each grid point in terms of the climatic conditions and the snow or ice cover, and sea surface temperatures are held at their monthly mean values. Even for short-period forecasts of two to three days, it is necessary to compute the heat lost by the atmosphere through long-wave radiation to space and the long-wave transfer between model layers including the effects of clouds and the ground, otherwise predicted temperatures for the middle and upper levels are too high.

In addition to this hemispheric model, the Meteorological Office runs a finer-mesh model, described by Bushby and Timpson (1967), Benwell and Timpson (1968) and Benwell *et al.* (1971), with very similar dynamics and physics but with a horizontal grid length of only 100 km limited to a 6400 km $\times$ 4800 km rectangle centred on the British Isles. This provides more detailed forecasts for the United Kingdom and western Europe up to 36 hours ahead, is particularly useful in making quantitative predictions of rainfall from depressions and fronts, and distinguishes between widespread persistent rain and showery convective rainfall. Since the time-steps of the integration are one-third of those for the hemispheric model, the amount of computation, about 10^{10} numerical operations, is about the same, and takes about 10 minutes on the IBM 360/195 computer.

Both models are run twice a day using the noon and midnight observations according to the following operational sequence. When the weather observations from practically the whole of the northern hemisphere, amounting to about one million coded groups per day, arrive at Bracknell, they are automatically checked, quality-controlled, corrected, edited and arranged in suitable format for input to the

models by two dedicated smaller computers. The next stage is to produce analyses of the basic data and from these establish initial values of the dependent variables in the forecast equations. This involves the production, by various objective smoothing, curve- and plane-fitting techniques, of smooth continuous fields of contour heights and humidity mixing ratios from which can be extracted grid-point values over the whole area and for the 10 levels. The analysed fields are now subjected to an 'initialization' procedure to ensure consistency between the contour and wind fields. This involves the solution of two equations, one dealing with the non-divergent component of the wind field and the other with the divergent component and hence the vertical motion, to produce 'best' initial values of the contour height and the three wind components. These parameters together with grid-point values extracted from a smoothed initial humidity field are sorted in column format together with geographical, topographical and climatic constants, surface temperature and humidity parameters, to provide the starting conditions for step-wise integration of the predictive equations.

3. Example of a five-day numerical forecast

By way of example, we shall now describe a series of computer forecasts predicting the marked change of weather that took place over the British Isles on 6 and 7 January 1979 when the spell of very cold weather that began on 30 December 1978 gave way to a rapid thaw. This change was well predicted by the hemispheric model from 3 January and the further westerly progress of milder air into north-east Russia during the following two days was also well forecast.

Figure 1 shows the surface weather map based on observations made at 12 GMT, 3 January 1979 when the weather was still very cold over the whole of the British Isles except north-west Scotland. Even the south-south-easterly winds over south-west England were very cold. There was no westerly flow over the Atlantic Ocean to bring milder maritime air into the country. The 24 h forecast valid for midday on 4 January—see Figures 2 (a)–(b)—indicated correctly that the depression to the south-west of the British Isles would move into France (its centre being very accurately placed with the central pressure predicted as 984 mb compared with the actual value of 980 mb), producing strong easterly winds on its northern flank. The mid-Atlantic ridge of high pressure was predicted to move eastwards and the deep depression over Labrador to move north-eastwards with the westerly airstream on its southern flank extending into the Atlantic.

Figure 3 (a) shows that by 12 GMT on 6 January westerly winds had reached most of the British Isles and within 24 h the thaw was under way. The 72 h forecast for the time, Figure 3 (b), indicated a breakdown of the mid-Atlantic ridge allowing the westerly winds with their associated troughs of low pressure to progress and cover the northern half of the British Isles. Although this forecast did not anticipate the development of the anticyclone over continental Europe and of the depression over the Mediterranean particularly well, it gave a good indication of the breakdown of the cold weather regime. Figure 4 (a), a chart of the actual situation at 12 GMT on 8 January, shows that by this time the westerlies and associated troughs covered the North Atlantic and the whole of Scandinavia whilst a new depression was approaching Newfoundland from the west. These developments were all indicated in the forecast made five days earlier depicted in Figure 4 (b) which is the 120 h forecast for 12 GMT, 8 January, based on observations made at 12 GMT on 3 January.

4. Precision and accuracy

The precision to be attempted and the accuracy likely to be achieved in predicting the location and timing of a particular weather feature will be dependent upon the time range of the prediction, on the scale and life-time of the weather systems involved, and on the spatial resolution of the forecasting

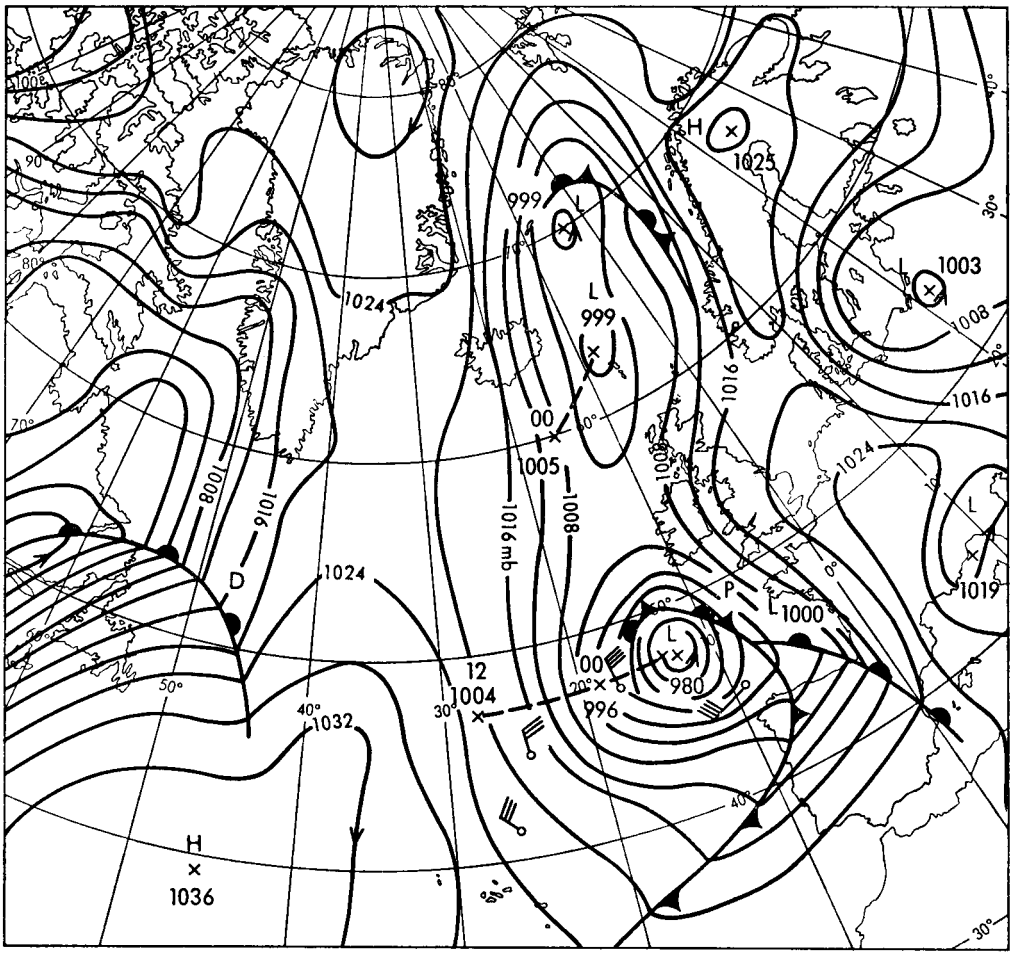

Figure 1. The actual surface weather map drawn from observations made at 12 GMT on 3 January 1979. All the forecasts shown in subsequent diagrams are based on the observations made at this time.

model. Thus the fine-mesh model described earlier will predict the geographical position and central pressure of a major cyclone 1000 km in diameter and lasting for five to six days within 50 km and 2 mb respectively. For a forecast made for only 24 hours ahead it is reasonable to attempt this degree of precision in relation to the accuracy achieved. However, the errors grow roughly exponentially as the forecast period is extended, so that although the model will continue to produce a deterministic and apparently precise forecast, precision and accuracy progressively diverge, and beyond five to six days the accuracy at the present time usually falls below useful limits.

At the other end of the scale, prediction of the location, movement and intensity of individual shower clouds, only 1–10 km in diameter and lasting for <1 hour, is impossible with present models which lack the requisite small-scale physics, observations and resolution. The best that can be done is to predict where and when the atmosphere is likely to become convectively unstable within a layer of

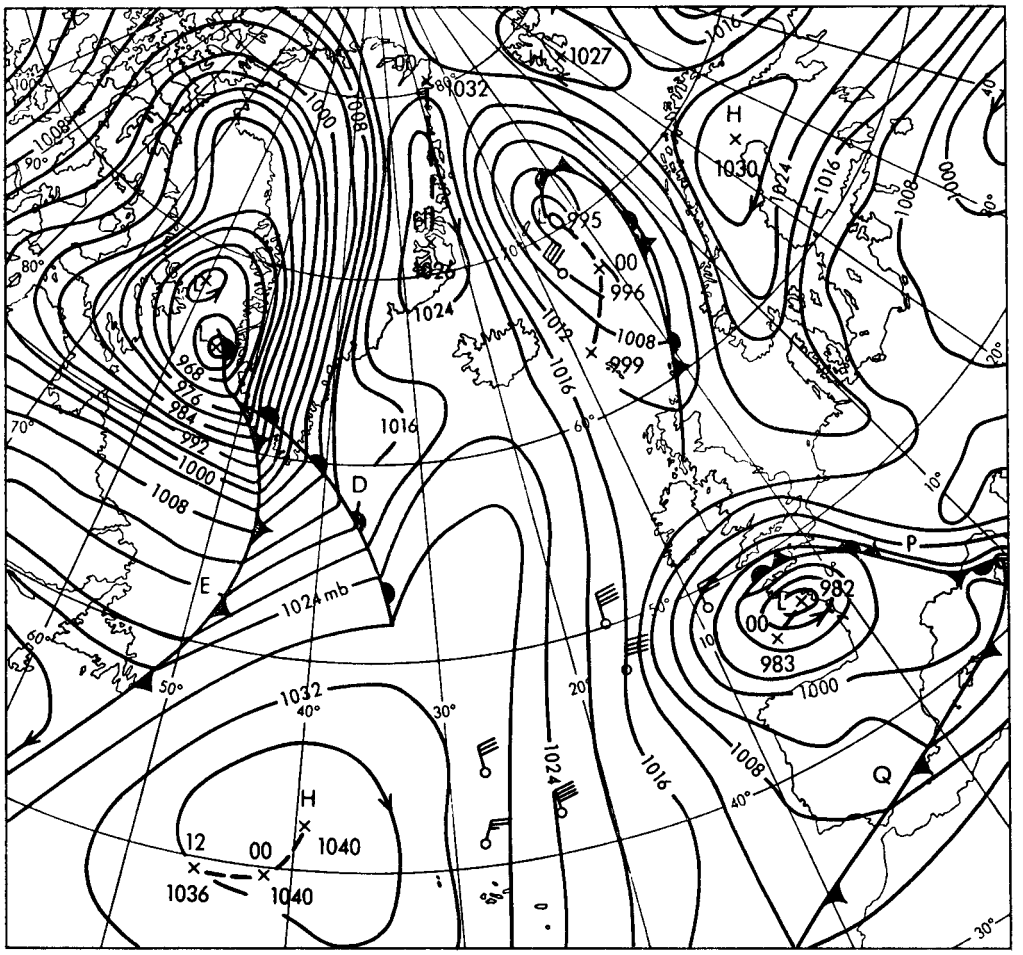

Figure 2(a). Actual surface weather map for 12 GMT, 4 January 1979.

restricted depth and so liable to sporadic outbreaks of showers, but there is no possibility of predicting exactly where and when a shower will actually appear. The forecast may then perforce take the form of say, 'a high risk of scattered showers, mostly light and of short duration' since they are likely to be almost randomly distributed. Indeed, a shower having been accurately located by radar or satellite, its subsequent motion and development can best be predicted by extrapolation, not necessarily linear extrapolation, of its recent evolution.

In summary, it is not possible, by the intrinsic nature of the problem, to predict accurately the location of a small weather system for more than a short time in advance: precision may be possible at the expense of range, but a long-range forecast will necessarily be lacking in precision and detail. It is just not possible to achieve both precision and range in the same forecast.

The achievable accuracy for prediction on a particular time and space scale is limited by

(i) inadequacies in the coverage, frequency, accuracy and representativity of the observations used to define the initial state;

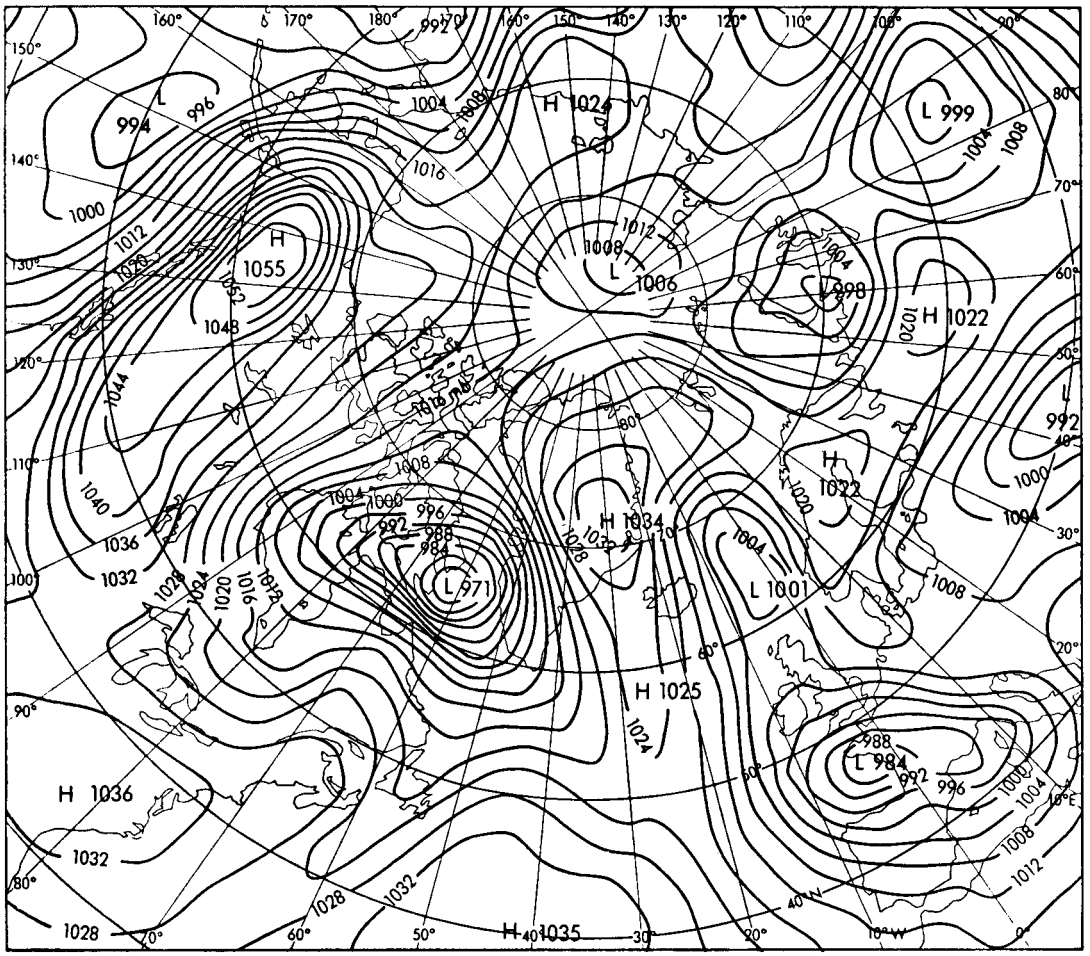

Figure 2(b). 24 h computer forecast for 12 GMT, 4 January 1979.

(ii) neglect in the models of some of the physical processes, especially small-scale processes, or their inadequate statistical representation;

(iii) computational errors which arise at each time-step of the integration and so build up cumulatively;

(iv) random fluctuations in the real turbulent atmosphere which are not represented in the model.

Although the models themselves are far from perfect, serious errors in short-range (one- to five-day) weather predictions probably arise mainly from the lack of adequate observations, especially from over the oceans and remote land areas. Accurate longer-range predictions for a week or more ahead may not be possible without allowing for interaction between the atmosphere and at least the surface layers of the oceans that may produce anomalies in sea surface temperature relative to the long-term average values. As to model deficiencies, it is difficult to distinguish between the effects of numerical errors introduced by the finite-difference approximations to the continuous dynamical equations and those

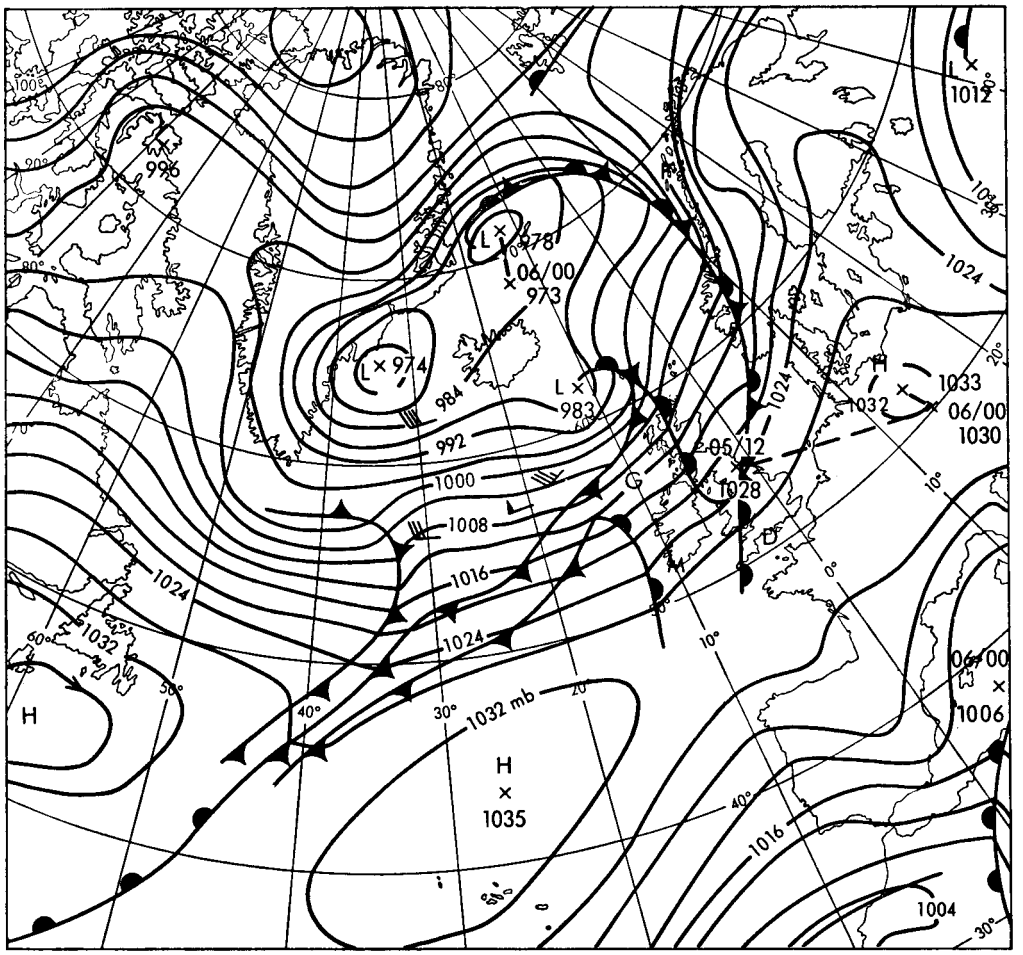

Figure 3(a). Actual surface weather map for 12 GMT, 6 January 1979.

that arise because the equations themselves do not provide a complete and exact description of atmospheric behaviour, but the two sources of error appear to be of comparable importance. Some of the more important deficiences arise from inadequate horizontal and vertical resolution and from inadequate representation of topography, precipitation, convection, horizontal eddy viscosity and surface drag. All require a good deal more research.

5. Verification and evaluation

While there is naturally much public interest in the accuracy of weather forecasts, their utility and economic value excites less comment, yet both accuracy and usefulness are important if forecasts are to be used to maximum advantage. It is convenient to distinguish between *verification* in which the emphasis is on the degree of goodness of the forecasts when compared with the actual weather during the forecast period, and *operational evaluation* in which the forecasts are judged in terms of their value

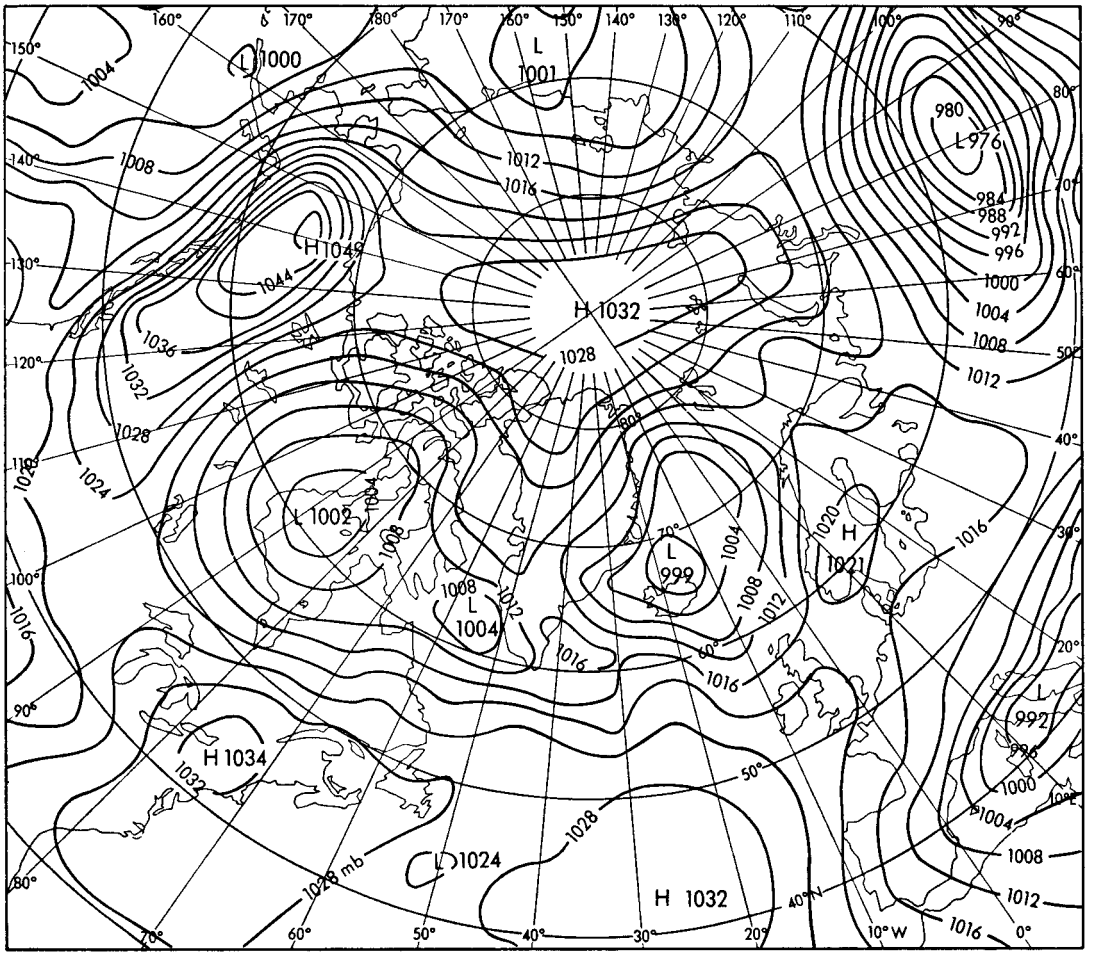

Figure 3(b). 72 h computer forecast for 12 GMT, 6 January 1979.

or utility to the user. Verification of forecasts is undertaken by the Meteorological Office as a routine activity to provide an overall measure of the performance and effectiveness of the prediction models and techniques and to monitor the effects of changes introduced from time to time.

Many different types of forecast are issued to serve a wide variety of customers. Forecasts for the general public, disseminated mainly by television, radio and the press, are largely expressed in words. The two million forecasts made each year for civil and military aviation, and the tailor-made forecasts for such weather-sensitive industries as electricity, gas, shipping, and offshore oil and gas are usually presented in numerical form or by specially prepared charts. Meteorologists themselves make great use of prognostic charts, often the output of the numerical models and drawn by computer, of the expected distributions of atmospheric pressure, temperature, winds, rainfall, etc. An assessment of their accuracy can be made by comparison of forecast and actual values at a three-dimensional network of grid points and is an objective and fairly straightforward exercise. Forecasts expressed in words have to be assessed

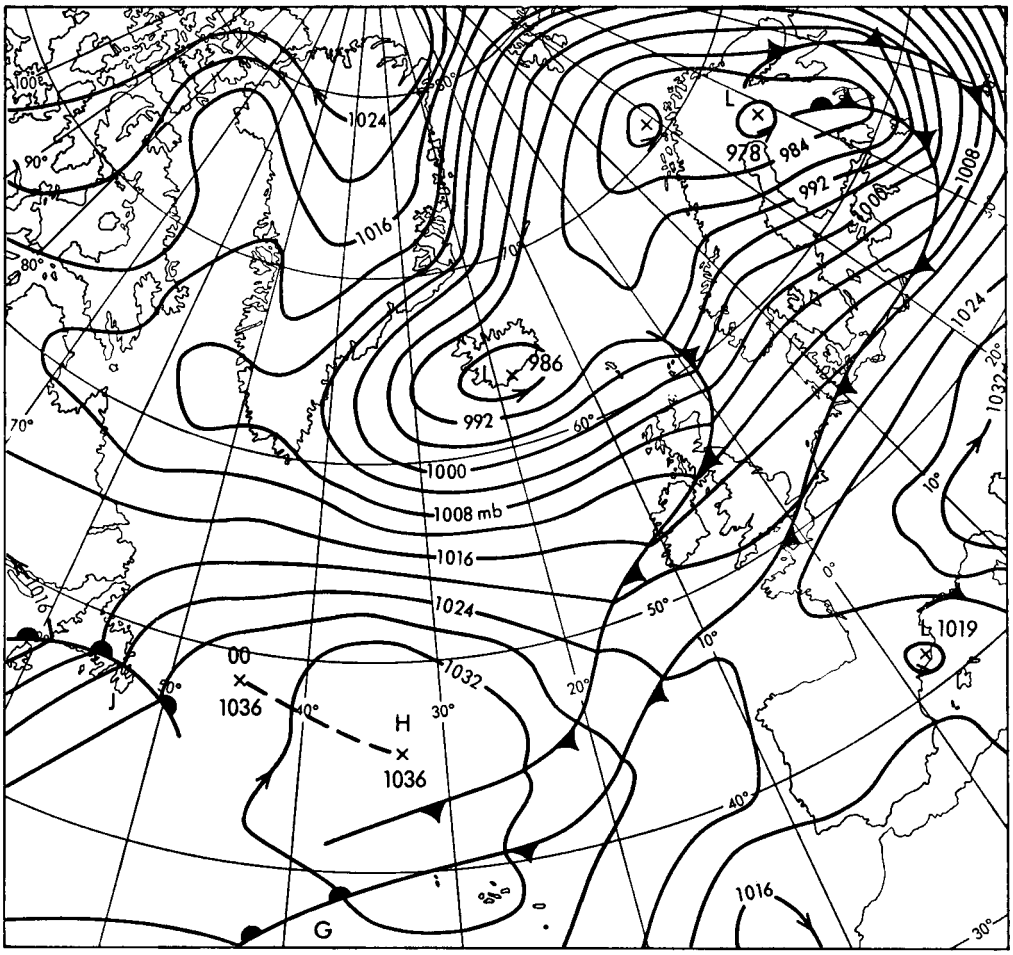

Figure 4(a). Actual surface weather map for 12 GMT, 8 January 1979.

subjectively and the results are inevitably less precise and more difficult to interpret. In an attempt to bridge the gap the Meteorological Office is conducting some experiments in which a computer is programmed to produce objective, worded forecasts from the output of the numerical prediction models.

A decade ago, before the introduction of advanced computer models, forecasts were rarely issued for more than 24 hours ahead and were less detailed and less accurate than those of today. The numerical methods have led to a greater degree of continuity, consistency and confidence in the forecasts than existed when they depended entirely on the personal experience and judgement of changing rosters of forecasters. Perhaps the single largest contribution of the numerical models has been to extend the range of surface forecasts from one to three days and to provide useful guidance up to six days ahead.

In the objective assessment of numerical forecasts, much attention is given to the forecast chart of the distribution of atmospheric pressure at the earth's surface on which weather forecasts for the general public are largely based. One standard test is to compare the predicted height of the 1000 mb pressure

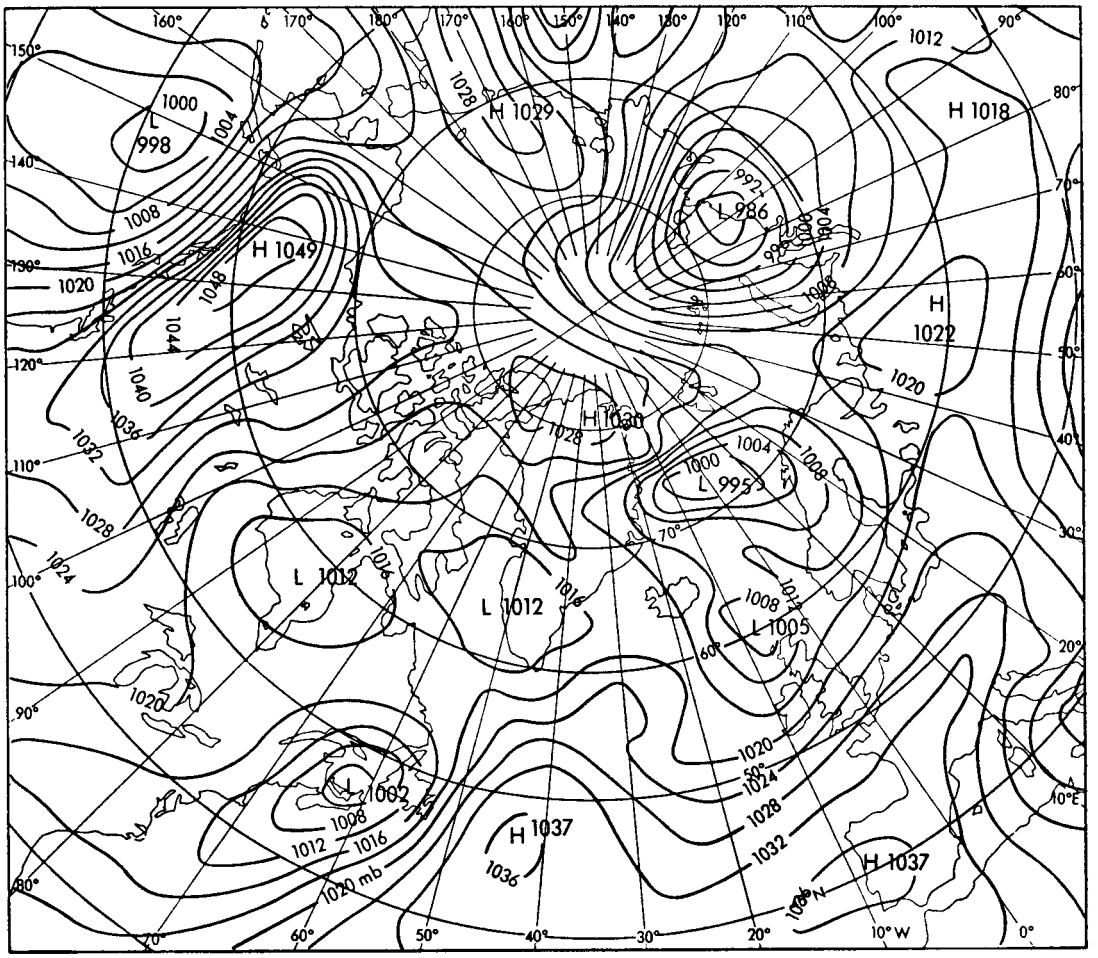

Figure 4(b). 120 h computer forecast for 12 GMT, 8 January 1979.

surface at a large number of grid points with the corresponding heights on the 'actual' or verifying chart and then calculate the mean height error or 'bias' and the root mean square (r.m.s.) height error. Since it is a simple matter to derive the geostrophic winds from the pressure distribution, the r.m.s. vector wind error, which takes account of errors in both speed and direction of the wind, is also calculated*. The results of the analysis, some of which are shown in Figure 5, indicate that the mean height error or bias has now been almost entirely eliminated in surface forecasts up to 72 hours ahead whilst the r.m.s. height and vector wind errors have been substantially reduced so that the 72 h and 48 h forecasts are now about as good in these respects as the 48 h and 24 h forecasts were a decade ago. The statistics also show a marked improvement in forecast performance soon after the introduction of the

*This is a stringent test because, for example, a forecast wind of 30 kn ($\approx$ 15 m s^{-1}), exact in magnitude but with a 30° error in direction, would have a vector error of 15 kn ($\approx$ 7·5 m s^{-1}).

ten-level models in August 1972 and a continuing steady improvement ever since. Figure 5 shows that the correlation coefficient between the forecast and observed 72 h changes in the height of the 1000 mb pressure surface increased from only 0·32 to 0·65 during 1972/73 and has since increased to 0·72, whilst the correlation for 24 h changes has improved from 0·77 to 0·85.

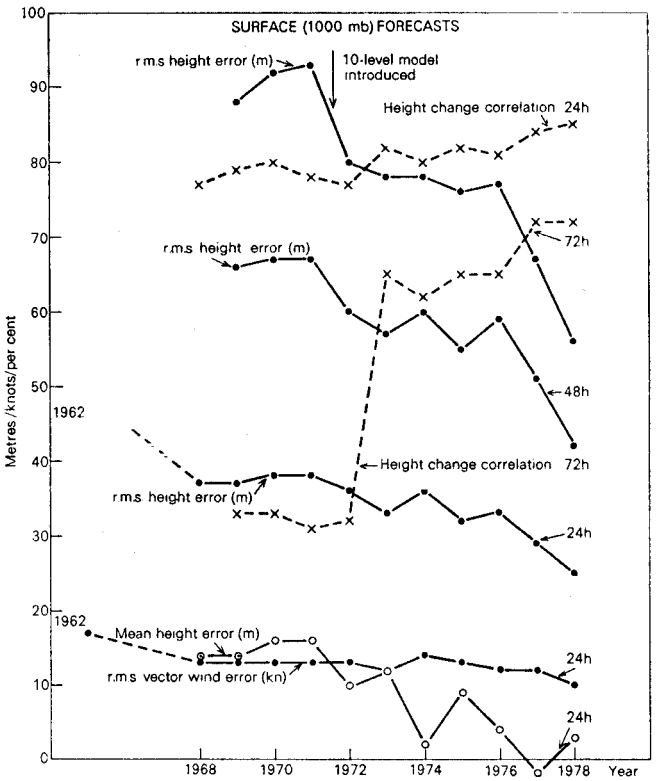

Figure 5. Errors in numerical forecasts of the height of the 1000 mb pressure surface and of the geostrophic winds, showing continual improvement over the last decade.

Predictions of air temperature made 24 h in advance for the 1000 mb pressure surface of the hemispheric ten-level model show r.m.s. errors of about 3 K. However, these predictions may be improved by allowing for additional factors such as cloud cover and local effects so that 90 per cent of the 12 h forecasts and 80 per cent of the 24 h forecasts issued to the Gas and Electricity Boards are correct within ± 2 K, only 1 per cent and 4 per cent respectively being in error by more than 5 K.

Even the first operational numerical three-level model introduced in November 1965 proved markedly superior to subjective methods in forecasting winds and temperatures at upper levels for aviation and soon thereafter all such forecasts were based on computer methods. Numerical values of the forecast parameters are fed directly from the Meteorological Office computer into the airline computers for flight planning and also provide the basis of the meteorological advice (flight documentation) issued to

aircrews. The numerical methods have led to the r.m.s. vector errors in the 24 h forecasts of winds at 500 mb (18 000 ft) and 200 mb (40 000 ft) being halved from about 30 kn to about 15 kn. The 48 h forecast errors of about 20 kn and the 72 h errors of about 25 kn are now very little larger than those of the corresponding 24 h and 48 h forecasts only five years ago. Similar improvements appear in the r.m.s. height errors and the mean height errors have now been reduced to only a few metres. Again, as shown in Figure 6, marked improvements followed the introduction of the 10-level model which also produces better forecasts of the location and strength of the high-level jet streams.

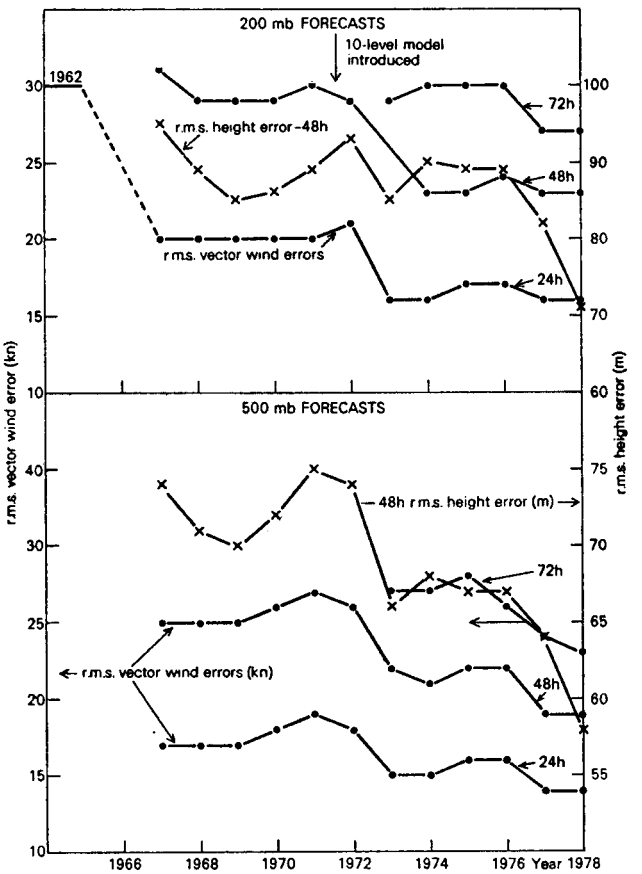

Figure 6. Errors in numerical forecasts of winds at 500 mb (≈ 18 000 ft) and 200 mb (≈ 40 000 ft) and in 48 h forecasts of the height of those pressure surfaces.

Desirable standards of forecasting accuracy for civil aviation are set by the International Civil Aviation Organization (ICAO). They are: upper winds (at levels above 25 000 ft) within 20 kn vector difference on 90 per cent of occasions over a period of one hour's flying time and upper-air temperatures

within ± 3 K on 90 per cent of occasions. The average r.m.s. errors in the 24 h forecasts issued in 1978 were only 2 K and 14 kn at 500 mb and 3·5 K and 16 kn at 200 mb, and since errors evaluated along 500-mile tracks (equivalent to about one hour's flying) are smaller than those for spot values at grid points, it appears that the ICAO requirements are now being met except perhaps in the vicinity of jet streams and areas of sharply changing gradients.

For longer-range model predictions, for up to six days ahead, the r.m.s. vector errors in the forecast winds at 500 mb, which average 16 kn after 24 hours, double during the next three days but are still below the errors of forecasts based on persistence after six days. A similar performance is achieved at the 1000 mb and 200 mb levels.

Whereas objective tests can be devised to assess the accuracy of numerical forecasts, it is much more difficult to assess written and spoken forecasts, which are largely descriptive, and here the approach has to be more subjective. The difficulty lies in deciding what weights should be given to the various elements of the forecast in arriving at an overall figure of merit for the forecast as a whole. Although it is possible to design sensible systems of awarding 'skill-scores' for individual parameters such as temperature, wind, precipitation, etc., it is much more difficult to combine these individual marks into an overall score for the forecast as a whole. This is mainly because the weighting of the various factors will be judged differently by different users and should probably vary with season and climatic regime. Thus a forecast which gets high marks for temperature and wind but is a few hours out in predicting the arrival of a rain belt may be regarded as a complete failure by a farmer concerned with getting in the harvest whilst a yachtsman or a power engineer may judge it more leniently. Or, to take another example, an error of a few degrees in the forecast minimum temperature may be unimportant and pass almost unnoticed in midsummer, but a similar error may have very serious consequences when the temperature is near freezing.

Since August 1963 the Meteorological Office has applied a simple marking scheme to the 0755 BBC forecast valid for the following 16 hours and the 1755 forecast valid for the following 30 hours. The forecasts for each of the seven regions are checked by selected Meteorological Office stations within the region. Each forecast is evaluated in terms of four parameters—wind speed and direction, weather (precipitation, fog, etc.), state of sky, and maximum temperature—each being awarded marks 2, 1, or 0 according to whether the forecast is regarded as correct, only partly correct, or incorrect. Since the scores turn out to be much the same for the four elements, an average mark is taken as a measure of the overall performance and avoids the difficulties of assigning different weighting factors to the various elements. Although the assessments are made at many different stations and by many individuals, there is a high degree of uniformity between the different regions. The 0755 forecast, as might be expected, is consistently more reliable than the 1755 forecast, the overall scores for 1978 being 86 and 78 per cent respectively.

These forecasts are based on guidance given by the Central Forecasting Office at Bracknell in country-wide 'synoptic reviews' issued some $2\frac{1}{2}$ hours earlier. They, in turn, depend heavily on the predictions of the numerical models and have shown marked improvements in recent years. Whereas 10 years ago less than half of these guidance forecasts were essentially correct and 1 in 7 were seriously misleading, since 1972 two-thirds have given good guidance and only 1 in 15 has contained serious errors.

The overall improvement in the two- and three-day surface weather forecasts in recent years, which again are largely based on the numerical prognoses, is apparent from Table I, showing the percentages of all forecasts falling within three performance categories.

Although these recent improvements may be attributed largely to the numerical models, the human forecaster still has a vital role to play in interpreting the computer products, in modifying them if he has good reason, and in predicting the behaviour of small-scale weather systems and local phenomena such

as thunderstorms, showers, fog, frost and ice which are not treated by the models. Indeed the improvements and advantages derived from numerical models may be largely nullified by forecasters lacking in experience and judgement of the real atmosphere.

Table I. *Evaluation of 48 h and 72 h surface forecasts.*

	48 h forecast			72 h forecast		
	A	B	C	A	B	C
	per cent			*per cent*		
1967	24	51	25	7	50	43
1972	51	37	13	27	45	28
1976	53	37	10	27	43	30
1977	59	32	9	31	46	23
1978	63	28	9	36	41	23

A—essentially correct. B—some errors, but none serious over the United Kingdom. C—misleading in some important respect.

6. Limits of atmospheric predictability

We now raise the crucial question of whether there is for each scale of atomspheric motion a finite intrinsic time range of predictability beyond which it is not possible to make a deterministic forecast. This question is of fundamental importance for practical weather forecasting because the answer may set ultimate limits to what is achievable and to what is worth aiming at.

Smagorinsky (1969) has posed the question as follows: 'If we had a physically faithful model of the real atmosphere, an ability to specify fully the initial conditions for all spectral components, and committed no truncation error in numerically integrating the system of non-linear differential equations, could we expect to predict the atmospheric evolution from an initial state with infinite precision infinitely distant into the future? Or, would small random perturbations (noise) develop in the model and amplify to the point at which numerical simulation departs from reality and ultimately become uncorrelated with the real atmosphere?' An answer to these questions might set an ultimate time limit to predictability beyond which no improvement, whether in models, initial conditions (observations), or computing power would increase the predictability of a given scale of atmospheric development.

Leading authorities such as Lorenz (1969) and Leith (1971, 1978) hold that a definite limit to predictability is set by the inherent instability of atmospheric motions and by their inherent non-linear and dissipative character. Robinson (1967, 1978) goes further and asserts that the modified Navier–Stokes equations (1–3) cannot be used to predict the mean motion of an atmospheric disturbance of horizontal scale L for times $t > L^2/K$ because it will lose its identity through the dissipative action of smaller eddies collectively represented by the lateral eddy diffusion coefficient K. Arguing on dimensional grounds that $K \approx L\bar{U}$, where $\bar{U}$ is the mean horizontal velocity of the flow, he arrives at a prediction time limit $t \approx L/\bar{U}$ which is equivalent to saying that the prediction time cannot exceed the time taken for the system to travel about one wavelength. For a middle latitude depression (cyclone) of $L =$ 5000 km travelling at $U = 20$ m s^{-1}, this gives a time limit of *c.* 3 days. Extensive experience with operational forecasting models shows this estimate to be too pessimistic. It is possible to predict the evolution of systems over considerably longer times than it takes to displace them by one wavelength. It is possible to predict major depressions for at least five to six days ahead (see section 3) with even the present imperfect models and inadequate observations. Moreover, the models are able to predict the formation and development of depressions and even fronts which are not present or detectable in the

smoothed fields of the initial state. The unreality of Robinson's treatment is further illustrated by its conclusion that finer resolution of the observational or computational grid would actually *reduce* the predictability time for larger-scale motions whereas experience shows that higher resolution leading to better description and prediction of the smaller scales also leads to improved simulation of the larger scales such as the planetary long waves.

A similar examination of the Navier–Stokes equations has been made by Leith and Kraichnan (1972) but treating the basic flow in spectral form and using a different closure hypothesis with a scale-dependent damping factor that ensures that interactions involving the smaller scales are heavily damped. They then define the predictability time as the time taken for the 'error energy' on any one scale to grow to one-half of the energy of that scale and arrive at periods at least 20 times greater than those of Robinson!

It is important to realize that these and similar analyses, which have attracted much attention and discussion, apply to predictions, from initial values, of the motions of an *unbounded* fluid in which motions of all scales are treated as decaying isotropic turbulence losing energy solely through a cascade of progressively smaller eddies and ultimately by molecular viscosity. Such a system has little in common with the real atmosphere which is bounded and largely forced from the planetary surface containing major energy sources and sinks, and in which quasi-two-dimensional baroclinic disturbances such as the mobile cyclones and anticyclones tend to become stabilized through non-linear interactions with smaller scales, the latter being able to transfer energy to the larger-scale motions as well as dissipate it through small-scale turbulence. Moreover, large-scale forcing of the atmosphere as the result of differential heating, thermal contrasts between land and ocean, the large thermal capacity of the oceans and rotation of the earth tends to impose preferred scales of motion and confer stability especially at longer wavelengths.

For all these reasons atmospheric motions are almost certainly predictable over longer periods than Robinson's highly artificial calculations for an unforced system of decaying isotropic turbulence suggest. It is, however, very difficult to derive a convincing theoretical criterion for the predictability of a system as complex as the real atmosphere, so we have to appeal either to its observed behaviour or to the results of experiments with numerical models.

One approach is to determine from observations for how long the structure and evolution of weather systems are influenced by the initial state. The effects of such persistence may be measured by correlations between two sets of observations made at increasing time intervals apart. Tests made with seven surface and upper-air observed parameters analysed on the spatial grid of the Meteorological Office five-level global model indicate correlation coefficients of about 0·3 for observations made 10 days apart but falling to less than 0·1 for data sets 30 days apart.

Another way of studying predictability is to determine how fast small errors in the representatio n of the initial state will grow in a numerical model. The method involves running the model from a gi ven set of initial parameters and again after a small random error is added at each grid point and following how rapidly the two simulations or predictions diverge. Experiments of this type with global models usually find that the errors double within a period of 2–4 days and suggest an upper limit of a few weeks for the prediction of day-to-day weather variations. Thus Smagorinsky (1969) reports the result of a test with a nine-level global model with horizontal grid spacing varying from 320 km at the Equator to 640 km at the Poles. Comparison trials were made for an observed (January) initial state and for a perturbed state in which a random temperature fluctuation of standard deviation 0·5 K was added at all grid points at all levels. The standard deviation σ of the temperature error (difference between the predicted temperatures of two runs) grew exponentially during the first seven days with a doubling time of about $2\frac{1}{2}$ days and thereafter more slowly. Nevertheless, after three weeks, σ was still only

about half the asymptotic value of the standard deviation of the difference between the predicted and initial (unperturbed) temperatures which was 5·5 K and taken as a measure of the natural variability.

This result is rather similar to that obtained for the growth rates of r.m.s. vector wind errors in the Meteorological Office hemispheric forecast model described above, where the errors doubled in the first three days but were still below the persistence values after six days. Some recent tests by Rowntree (personal communication) with a Meteorological Office global five-level model for three winter seasons show that differences in the model atmosphere's evolution induced by changes in the initial data were detectable up to about three weeks later but thereafter any influence of the initial conditions was lost in the random noise. Moreover correlations between *predicted* and *observed* states, both represented by 10-day averages at grid points, fell sharply from about 0·5 for the first 10-day period to about 0·1 for the third period.

All these results tend to indicate an upper limit of about one week for useful deterministic predictions with present models and observations but it is reasonable to hope for an extension to perhaps two to three weeks as both the models and their initial data improve.

7. Future outlook

Although forecasts issued to the general public are usually limited to three days ahead, the hemispheric model is run up to six days ahead once a day and the results provide the basis for the weekly farming forecast issued every Sunday. Although the model remains stable for much longer periods, the detailed predictions tend to deteriorate rather sharply beyond the fourth or fifth day. Reliable forecasts for a week or more ahead, which would be of great economic value to weather-sensitive industries such as agriculture, building, fuel, power, water resources and food manufacture, will require improved models with higher resolution, better representation of the physics, especially of clouds and of convective, radiative and turbulent transfer processes, and improved mathematical methods of integrating the equations in order to limit both the amount of computation and the errors involved. Geographical extension of the model, perhaps to cover the whole globe, improved observations from the oceanic and tropical regions, and greater computing power will also be required. There are, however, *inherent* limitations in the predictability of atmospheric behaviour set by the cumulative effect of random, small-scale disturbances that cannot be directly observed or treated explicitly in the models. None the less, current research encourages us to think that it should be possible to forecast the evolution of major weather systems such as the mobile depressions of middle latitudes for about a week or 10 days ahead and to give a useful indication of general trends over periods of perhaps a month. In some recent experiments in which the model equations were integrated up to 50 days and the results averaged over 10-day periods, the development of the long planetary waves, which largely determine the general character of the weather over periods of several weeks, was predicted quite well. A clearer idea of the possibilities should emerge when the recently inaugurated Global Weather Experiment, which is to make a continual, comprehensive survey of the global atmosphere for a period of 18 months, provides the models with input data sets of unprecedented quality and coverage.

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Examples of snow prediction using the 10-level model

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Summary

The output of the fine-mesh (or rectangle) version of the Meteorological Office operational 10-level model was assessed for its value as a snow predictor during the week 9–15 February 1979. The actual weather for the week was compared with that forecast by the model, with particular attention to the predicted probability of snow in relation to the observed change-over from rain to snow over the United Kingdom. A similar comparison was made using forecasts of probability of snow corrected as suggested by Boyden for sea-level pressure and topographic height.

Introduction

The fine-mesh (rectangle) version of the Meteorological Office numerical forecast model produces forecast fields of various parameters as guidance to the forecaster. Amongst these fields are two that may be useful in predicting snow. These are the precipitation patterns and the 1000–850 mb thickness field. Two isopleths of 1000–850 mb thickness are output and are labelled 20 per cent and 80 per cent. These are the probabilities that the precipitation will fall as snow at sea level according to Boyden (1964).

It is realized that the value of the 1000–850 mb thickness that corresponds to a change from rain to snow will depend on whether the layer up to 850 mb is stable or unstable. A stable easterly airstream may have a temperature near zero degrees Celsius from the surface to 850 mb and produce snow at a relatively high thickness. Conversely a moist, unstable westerly with relatively low thickness may have a temperature of −8 °C at 850 mb and still not produce snow at 1000 mb. Also the height of the wet-bulb freezing level is probably the most reliable predictor of snow as this is more representative of the shallow layer near the ground which is usually the important region for melting or not melting the snow (see for example Lowndes *et al.* 1974). Unfortunately the rather coarse 100 mb layers of the 10-level model do not permit accurate prediction of this variable, so the 1000–850 mb thickness is used.

The week of 9–15 February 1979 was chosen for an investigation of the reliability of the 10-level model as a snow predictor. This was a particularly good week for a test as during this period snow or rain fell every day over a large part of England and Wales. During the first part of the week both forms of precipitation fell over different areas at the same time, allowing a boundary to be identified where a change from snow to rain occurred.

Pressure was low for much of the period to the south-west of Britain and fronts remained slow-moving over south and south-west England. Between the 11th and 14th two depressions moved east over northern France and the Channel, the second depression transferring the main centre of low pressure from south-west to south-east of Britain. This resulted in a return of very cold air to the whole of Britain and severe blizzards in eastern England.

Method of assessment of the model's snow predictor

The reported present weather over the United Kingdom from 00 GMT on 9 February to 18 GMT on 15 February 1979 was examined for every hour, and areas of snow were separated from those of rain or sleet. The boundaries between these snow areas and the rain areas, referred to as the snow-line in this paper, were compared with the forecast snow probability lines. Thus a snow-line could be identified with an interpolated value of forecast snow probability. This identification was carried out at each

main synoptic hour using the forecasts (i.e. T + 12, T + 18, etc.) valid at that time. This process yielded about 60 values of the forecast snow probability that corresponded with snow-lines during the week in question. Four sets of such values were produced as follows:

(a) A set of values obtained from the operational forecast charts, i.e. using 20 and 80 per cent snow probability lines derived from 1000–850 mb thickness.

(b) A set obtained from charts including a 50 per cent probability line to give a more accurate interpolation than between the 20 and 80 per cent lines of the operational output.

(c) A set obtained by using Boyden's corrections for sea-level pressure applied to the thicknesses (50 per cent probability lines were also drawn on the charts).

(d) A set obtained from charts including a 50 per cent probability line but with Boyden's corrections both for sea-level pressure and for topographic height. The heights used for correcting the thickness are averages for each 100 km square of the rectangle grid.

The fully corrected thickness (h_1') for these charts was then

$$h_1' = h_0' + (h_{10} - H)/30 \qquad (1)$$

where h_0' is the uncorrected 1000–850 mb thickness (as used in sets (a) and (b)), h_{10} is the height of the 1000 mb surface above sea level, and H is the height of the ground above sea level. This formula is empirical and was derived by Boyden (1964).

Additionally the forecast snow probabilities were compared with the probabilities obtained from the objective analysis of the 1000–850 mb thickness at 00 and 12 GMT each day to assess the accuracy of the predicted thickness. The forecasts were also examined for their accuracy of precipitation area since obviously one needs precipitation as well as a suitable probability before snow can be forecast.

Discussion and results

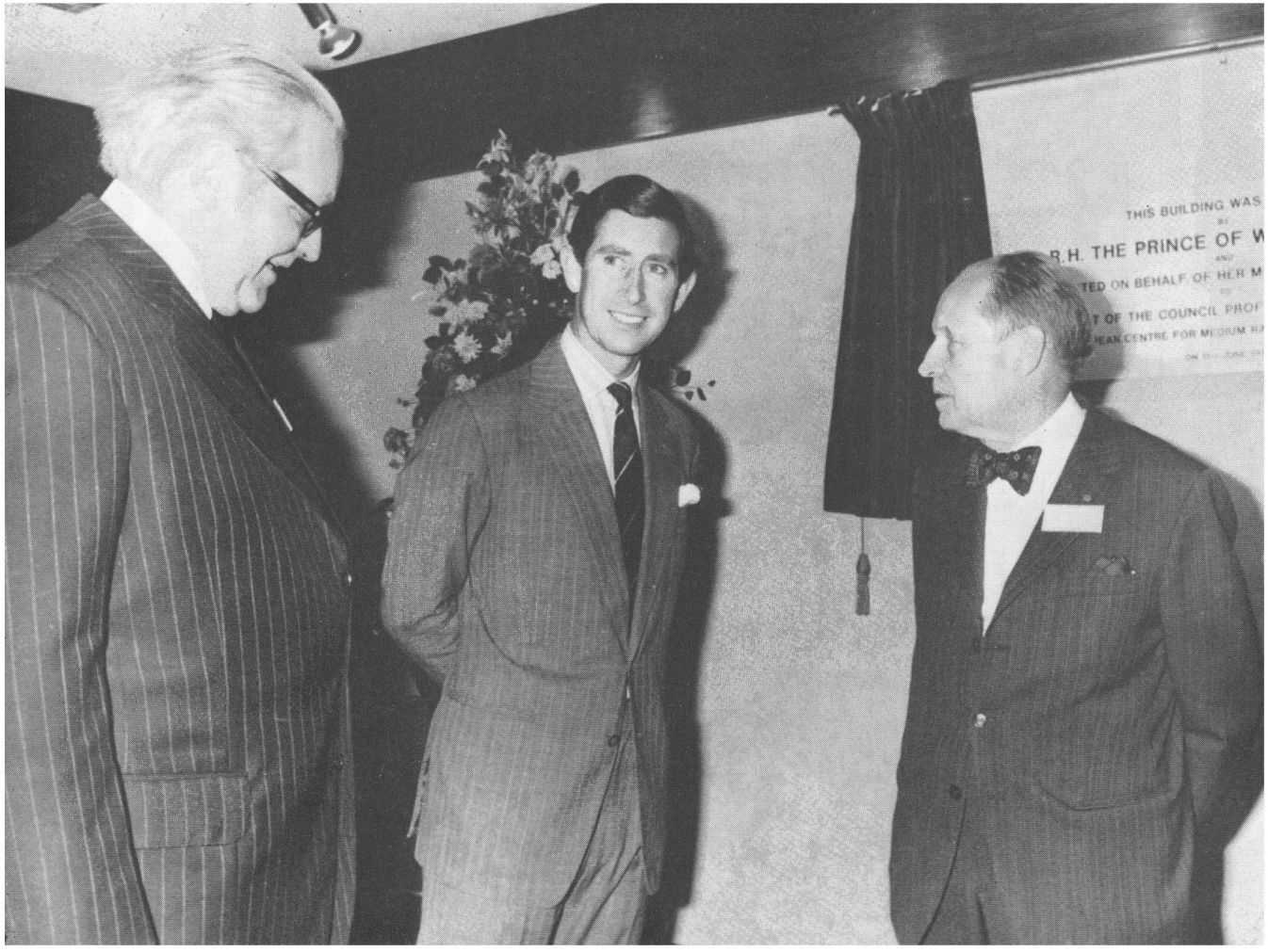
In general the precipitation areas were fairly well forecast during the week, the only inaccurate period being 06–12 GMT on the 11th when most forecasts predicted significant precipitation over the south and south-west of England. In fact there was only light and sporadic rain in this area and very little elsewhere during this period.

It is interesting to note that errors in precipitation forecasts can lead to errors in thickness forecasts. The forecast model (Burridge and Gadd, 1977) includes mechanisms for cooling a layer both by evaporation of precipitation and melting of snow. If, for example, precipitation is forecast by the model and forecast temperatures and humidities are such that either of these cooling effects can occur, the forecast thickness will be too low if in reality no precipitation occurs. In short, an inaccurate forecast of precipitation results in an inaccurate forecast probability of snow.

Figure 1 illustrates this effect quite well. The precipitation which was erroneously forecast to spread north between 06 and 12 GMT on the 11th caused a decrease in forecast thickness and hence an increase in the probability of snow by something in excess of 30 per cent over southern England. Advection considerations would indicate little change in the thickness. The computer analysis for 12 GMT on the 11th (not shown) does in fact show the 20 per cent and 50 per cent probabilities in positions not far removed from the forecast for 06 GMT on the 11th, as would be expected, there having been no significant precipitation during this period. Throughout the week as a whole the contribution due to melting and evaporation of the precipitation appeared to increase the forecast probability by about 30–50 per cent for the forecasts studied, depending on the intensity of the precipitation. By studying the probabilities obtained from the objective analyses during the week and the way in which these were changed by precipitation, a value for the actual change in probability due to precipitation occurring was obtained.

Plate I. His Royal Highness the Prince of Wales and the Director-General of the Meteorological Office in the Central Forecasting Office at Bracknell (see page 64).

Plate II. His Royal Highness the Prince of Wales, Sir John Mason, and Mr D. E. Jones, Assistant Director (Central Forecasting), in the Central Forecasting Office at Bracknell (see page 64).



Photograph by the Press Association Ltd.

Plate III. The unveiling ceremony at the official opening of the European Centre for Medium Range Weather Forecasts on 15 June 1979. From left to right: the Director of the Centre (Dr A. C. Wiin-Nielsen), His Royal Highness the Prince of Wales, K.G., K.T., P.C., G.C.B., and the President of the Council of the ECMWF, (Professor L. A. Vuorela). (See page 64.)

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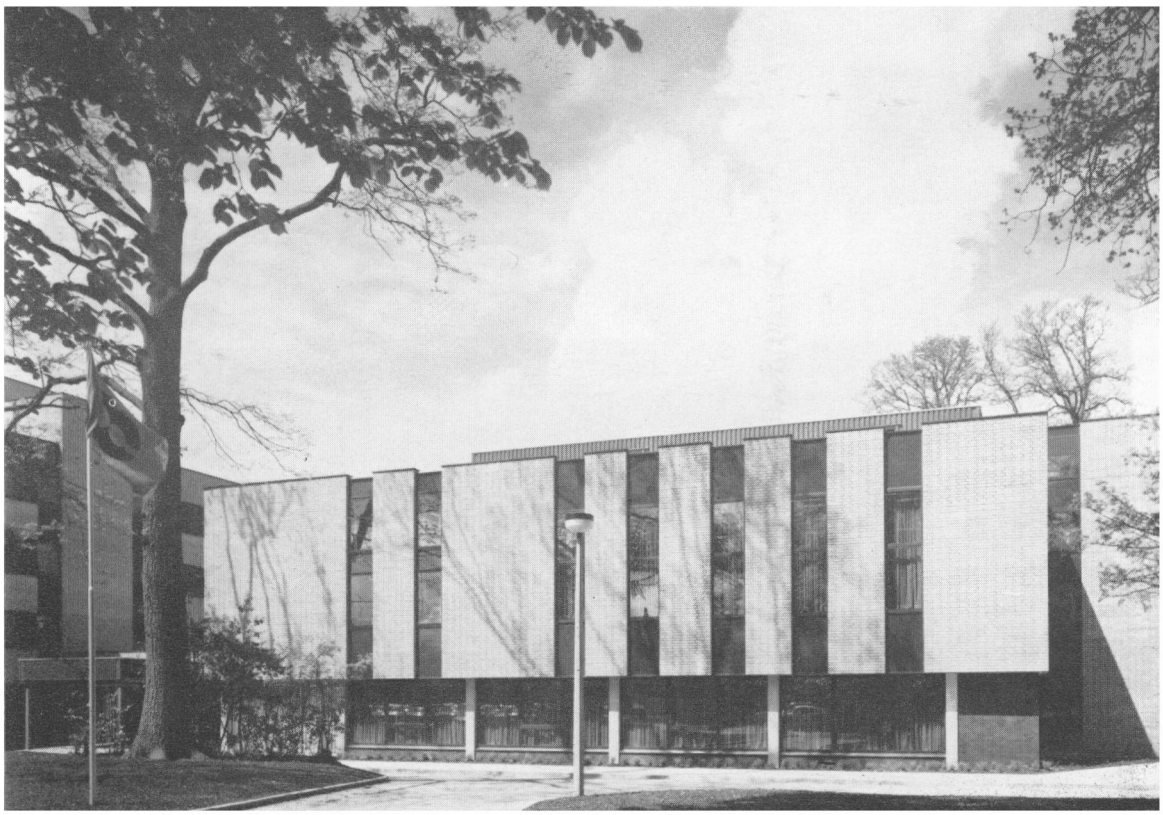


Photograph by the Department of the Environment

Plate IV. The European Centre for Medium Range Weather Forecasts, Shinfield Park, near Reading, Berkshire (see page 64).

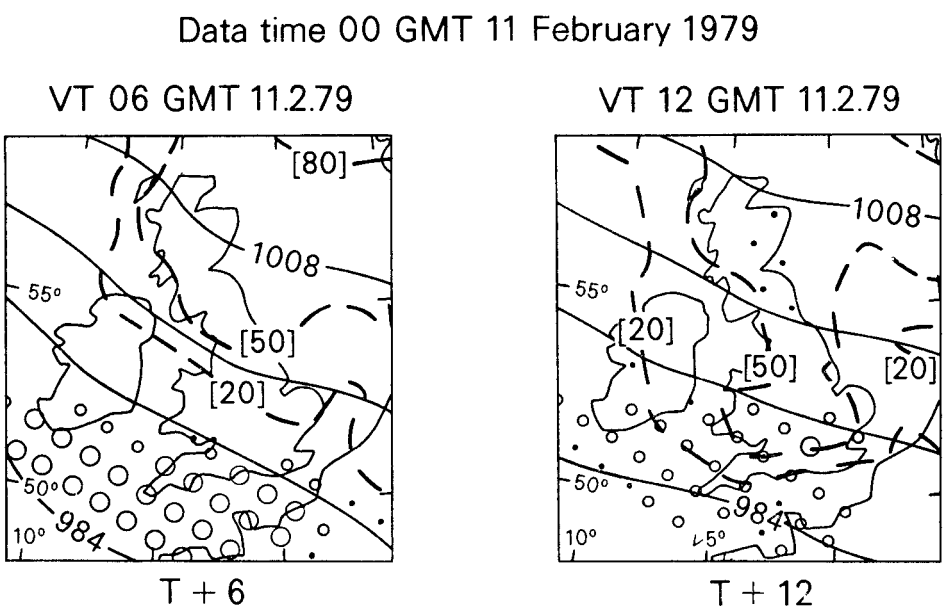


Figure 1. Example of the forecast cooling due to precipitation. Frontal rain (some dynamic rain forecast): O, o, • = total rainfall rate > 0·5, 0·1, 0·01 mm/h.
Showers (no significant dynamic rain): ▽, ∨, v = local convective rainfall rate > 4, 0·5, 0·1 mm/h.
Pecked lines represent 20, 50 and 80 per cent probability of snow, based on 1000–850 mb thickness.
Continuous lines are isobars at intervals of 8 mb. VT = verification time.

This value was around 30–40 per cent, indicating that the cooling forecast by the model was about right although possibly slightly too great for moderate or heavy precipitation.

Four histograms (Figures 2(a)–(d)) give the number of times a particular forecast snow probability corresponded with the snow-line. Figure 2(a) was obtained using the current operational chart output with 20 and 80 per cent probability lines, the values of probability between these values being interpolated to the nearest 10 per cent and thus being approximate. Figures 2(b)–(d) give more reliable values of probability as a 50 per cent snow-line was also drawn. Histograms were chosen as the pictorial representation of the results to highlight the approximate nature of their assessment.

Figures 2(a) and 2(b) show different distributions although the probability lines were derived from the same values of thickness. This difference results from the fact that the actual 50 per cent probability line lies much nearer the 20 per cent line, on many occasions, than an interpolated 50 per cent value, as used in Figure 2(a), between 20 per cent and 80 per cent. Thus a fixed distance on the forecast chart was interpreted as a 10 per cent range on the charts that produced Figure 2(a), whereas the same distance on the charts that produced Figure 2(b) produced up to 30 per cent probability range, resulting in a flatter distribution.

If a correction is made to the 1000–850 mb thickness to account for the height of the 1000 mb surface (i.e. a sea-level pressure correction) the mean value of the probability of the snow-line is nearer 50 per cent (Figure 2(c)). This follows since during the week in question pressure was generally below 1000 mb and the level at which snow was reported was thus nearer the freezing level than if pressure had been

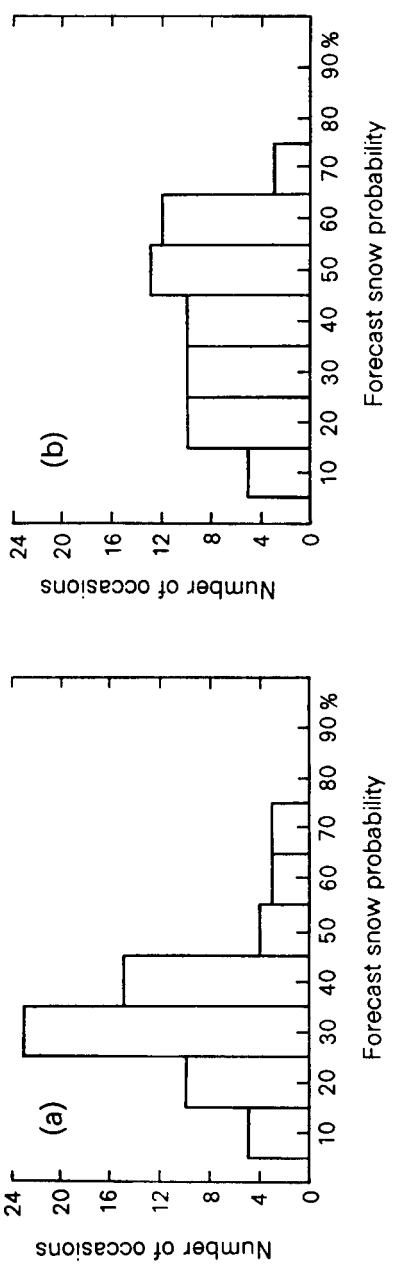


Figure 2. Number on occasions on which the snow-line coincided with various values of forecast snow probability.

(a) Probability not corrected for sea-level pressure or topographic height, and interpolated between 20 and 80 per cent isopleths.
(b) Probability not corrected for sea-level pressure or topographic height, but interpolated between 20, 50 and 80 per cent isopleths.
(c) Probability corrected for sea-level pressure and interpolated as in (b).
(d) Probability corrected for sea-level pressure and topographic height, and interpolated as in (b).

above 1000 mb. Boyden's correction adds a value to the probability to account for this. If mean sea-level pressure were above 1000 mb the mean probability of the snow-line would be expected to be lower than if pressure were below 1000 mb. So over a large number of cases, including both high and low surface pressure, a greater variability of the snow-line probability would result if no surface-pressure correction were made.

If a further correction is made for topographic height, the probability of snow increases yet again (Figure 2(d)). The mean value of the forecast probability of snow which corresponded with the snow-line for the week was then 62 per cent. One might expect this value to be near 50 per cent, i.e. half the time it would be snowing at those places on the chart where the predicted probability of snow was 50 per cent and half the time it would be raining, corresponding to the snow-line being greater than 50 per cent probability or less than 50 per cent probability. A possible reason for the value being greater than 50 per cent during the week was mentioned above with reference to the accuracy of precipitation forecasts. In this particular week there was a tendency for too large an area of precipitation to be forecast on occasions, hence giving too low a thickness or too high a snow probability. It also appears that the forecast cooling due to the precipitation may have been too great for moderate or heavy precipitation.

Interpretation of Figure 2 in terms of making a forecast is somewhat difficult since part of the range of probabilities over which the snow-line varies is due to forecast errors and part is due to the inconsistency of the 1000–850 mb snow predictor.

However, it does indicate the usefulness of this particular method of snow prediction as used in the 10-level model. Forecasters build up an experience of interpreting the forecast probabilities in terms of where snow is likely to occur. Thus a particular value of forecast probability may be used to indicate a boundary of snow with rain. Figure 2(a) was obtained from the operationally produced forecast charts of the week in question and suggests a value of 30 per cent forecast probability that the forecaster may use as guidance for the boundary. By suitable wording of the forecast indicating that snow is more likely in certain areas (e.g. over high ground or in the north) and before or after a certain time, or both, forecasts of snow can have a high success rate.

Some examples of forecast chart output

Two examples of actual weather and forecasts for the same time are given in Figures 3–6. Figure 3 gives the weather at 00 and 09 GMT as actually reported on 12 February. At 00 GMT it can be seen that precipitation has broken out over a large part of England with the snow-line lying through the south Midlands into East Anglia, the snow occurring to the north of it. As a point of interest, almost all forms of precipitation are being reported at this time: freezing rain, drizzle, hail, sleet, snow, ice pellets, snow grains and rain, showing the difficulty of giving accurate forecasts of precipitation; the hail and ice pellets were taken as snow for this investigation.

The two forecasts for this time (Figure 4) have predicted the area of precipitation fairly well, although the intensity is too light in most places. Without any corrections for sea-level pressure or topographic height the snow-line is seen to be between 20 per cent and an interpolated 40 per cent with a slight increase in this probability by 06 GMT, probably due to cooling by latent heat, i.e. moving the snow-line southwards. Figure 5 shows the same surface pressure and precipitation forecasts but with a 50 per cent probability line added and also with the thickness corrections applied, as in Equation (1). The main effect of these corrections is to increase the probabilities, as would be expected.

In both cases a similar increase in probability is forecast between 00 GMT and 06 GMT, as in Figure 4, suggesting that the snow-line will move southwards. The actual weather for 06 GMT showed that the snow-line had indeed moved south, with the rain over southern England having turned to sleet

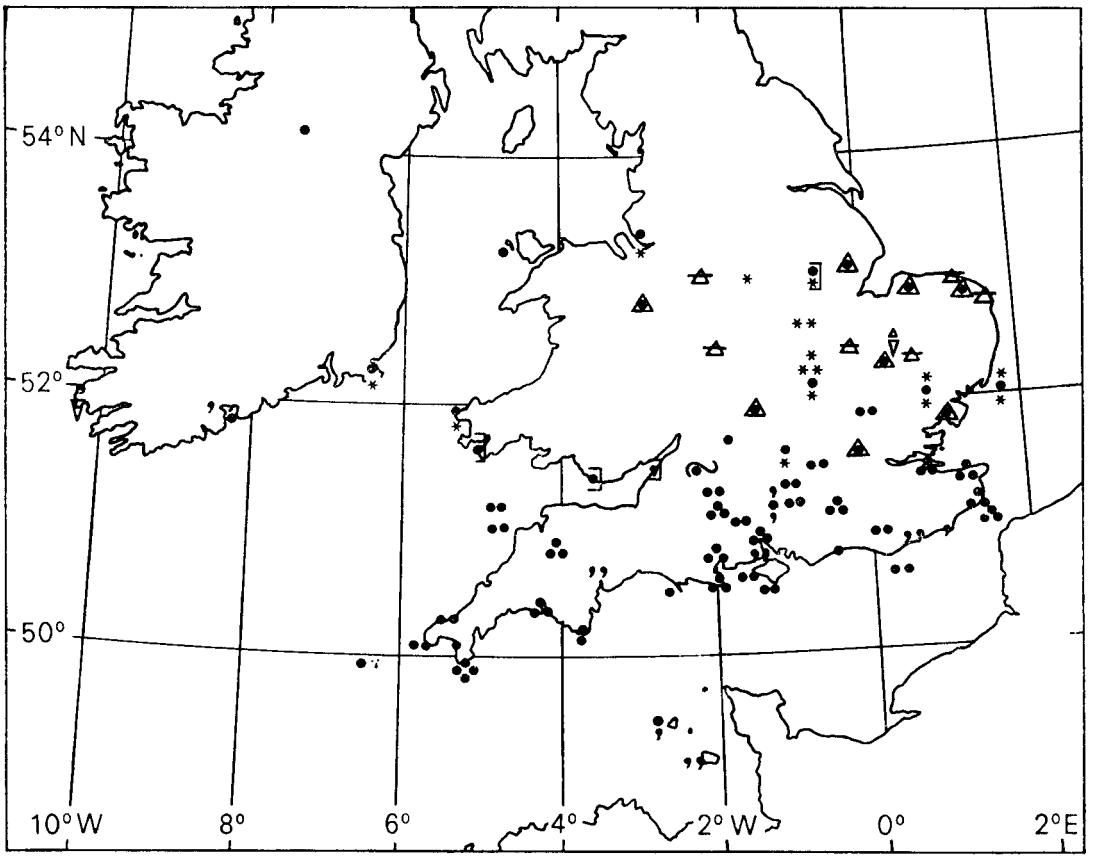


Figure 3(a). Weather at 00 GMT on 12 February 1979 over England, Wales and Ireland. The meanings of the conventional 'present-weather' symbols are given in the *Observer's Handbook*, third edition, London, HMSO, 1969.

or snow in many places. By 09 GMT (Figure 3(b)) the observations show that only a few of the stations reporting precipitation, mainly near coasts, are not reporting snow.

The second example is for 24 hours later (Figure 6); the two sets of operational forecast charts show the forecast snow-line (taken as its most frequent value of 30–40 per cent from Figure 2(a)) to have moved north again into North Wales and northern England. Observations for this time showed rain to be falling over southern England, with sleet over high ground, and snow in the north.

This snow in the north turned to rain in many places by 06 GMT except over high ground; this is indicated on the T + 18 forecast by a decrease in probability of snow.

The change from snow over much of England on 12 February to rain on the 13th could therefore be predicted quite well using the forecast snow probabilities produced by the rectangle. In fact, by using the 30–40 per cent forecast probability as a snow-line, the kind of sequence shown in Figures 3–6 could be forecast for much of the week.

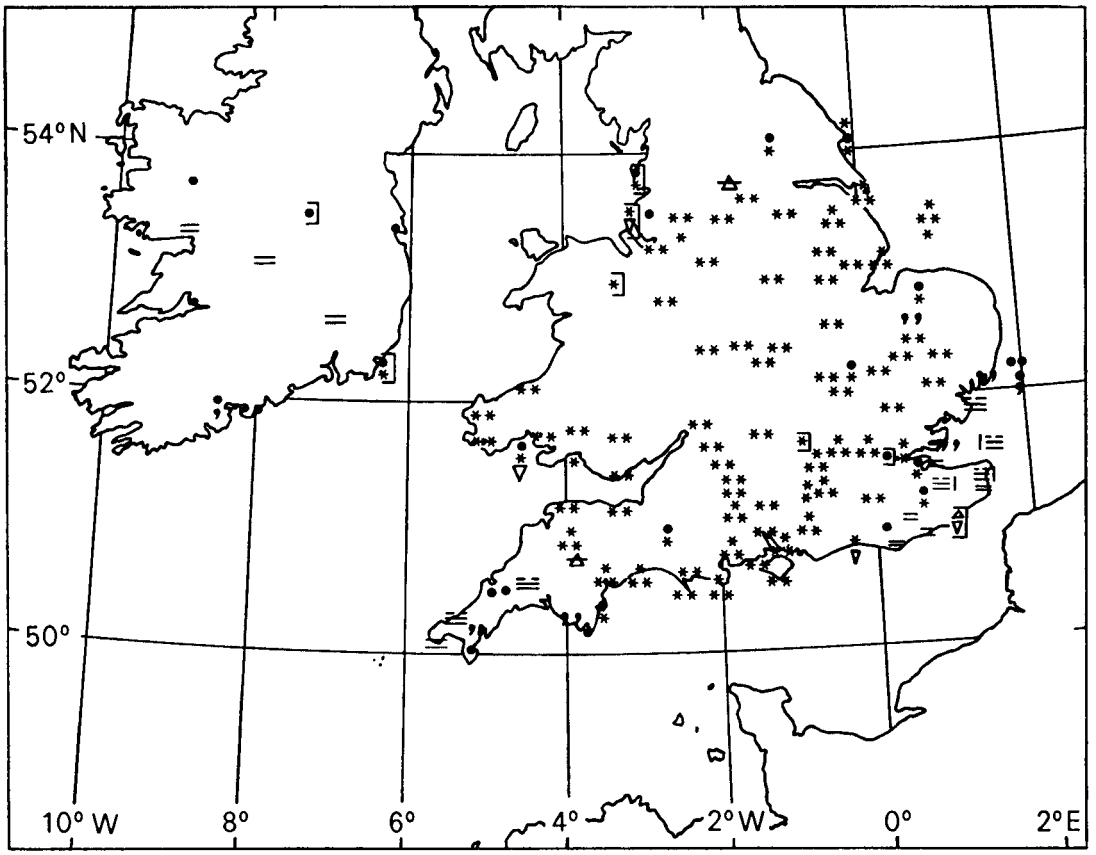


Figure 3(b). Weather at 09 GMT on 12 February 1979 over England, Wales and Ireland.

Conclusions

During the period 9–15 February 1979 the 10-level model (fine-mesh version) gave quite a consistent indication, from forecast 1000–850 mb thicknesses interpreted as probabilities of snow together with forecast precipitation areas, of where snow and rain would occur.

Snow occurred more often than rain where probabilities of snow were forecast to be greater than 30–40 per cent using Boyden's uncorrected values of 1000–850 mb thickness. By adding an extra 50 per cent probability line to this operational output the behaviour of the forecast model could be interpreted in greater detail: for example, the cooling effect by latent heat of evaporation and melting snow on the thickness of a layer could be discerned more easily.

If corrections were made to the forecast snow probabilities to account for variation of surface height and sea-level pressure, snow occurred more often than rain at forecast probabilities greater than 50 per cent when the pressure correction was applied, and greater than about 60 per cent when both corrections were applied.

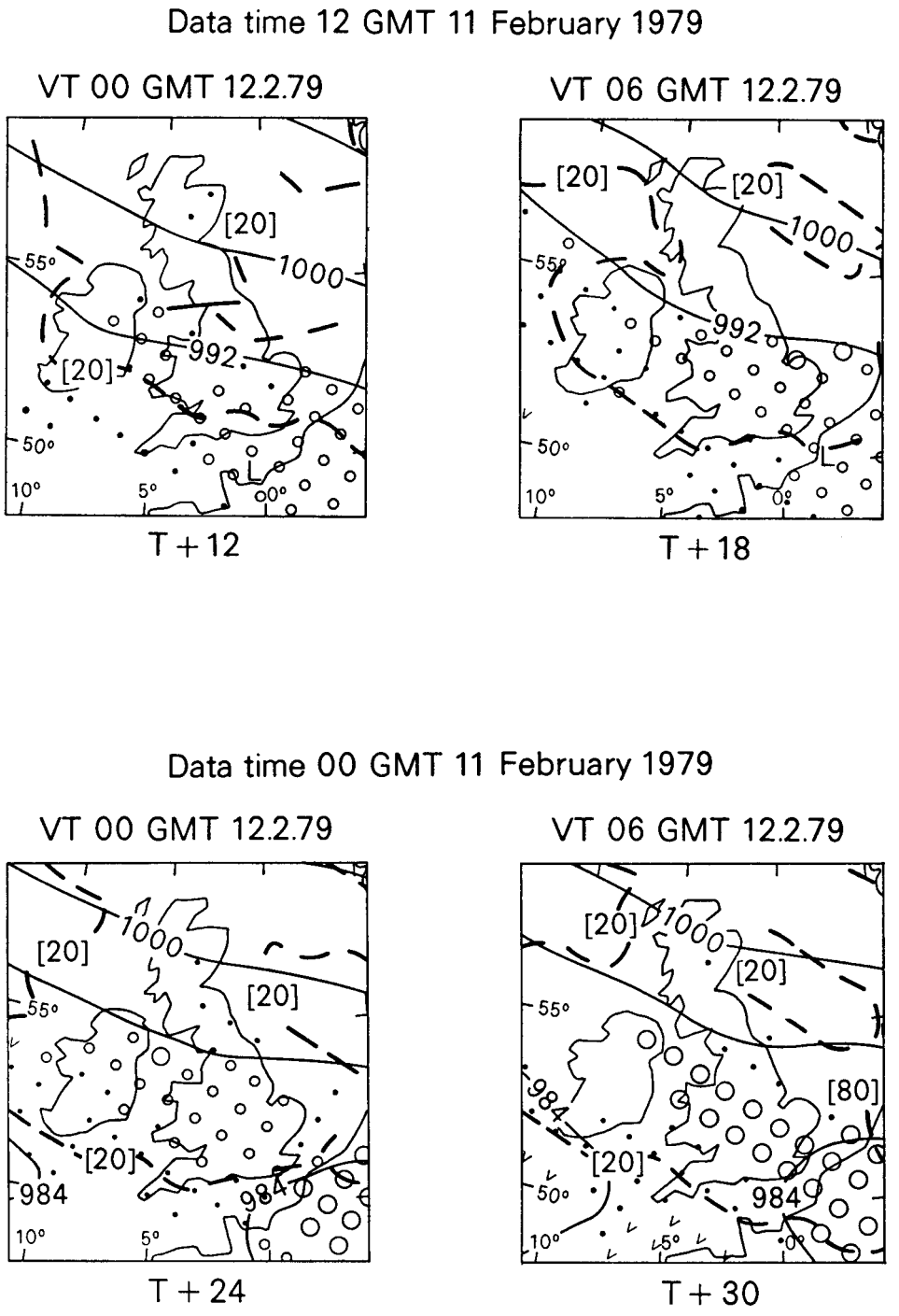


Figure 4. Operationally produced forecasts for 12 February 1979. Symbols and continuous lines as in Figure 1. Pecked lines represent 20 and 80 per cent probability of snow, based on 1000–850 mb thickness.

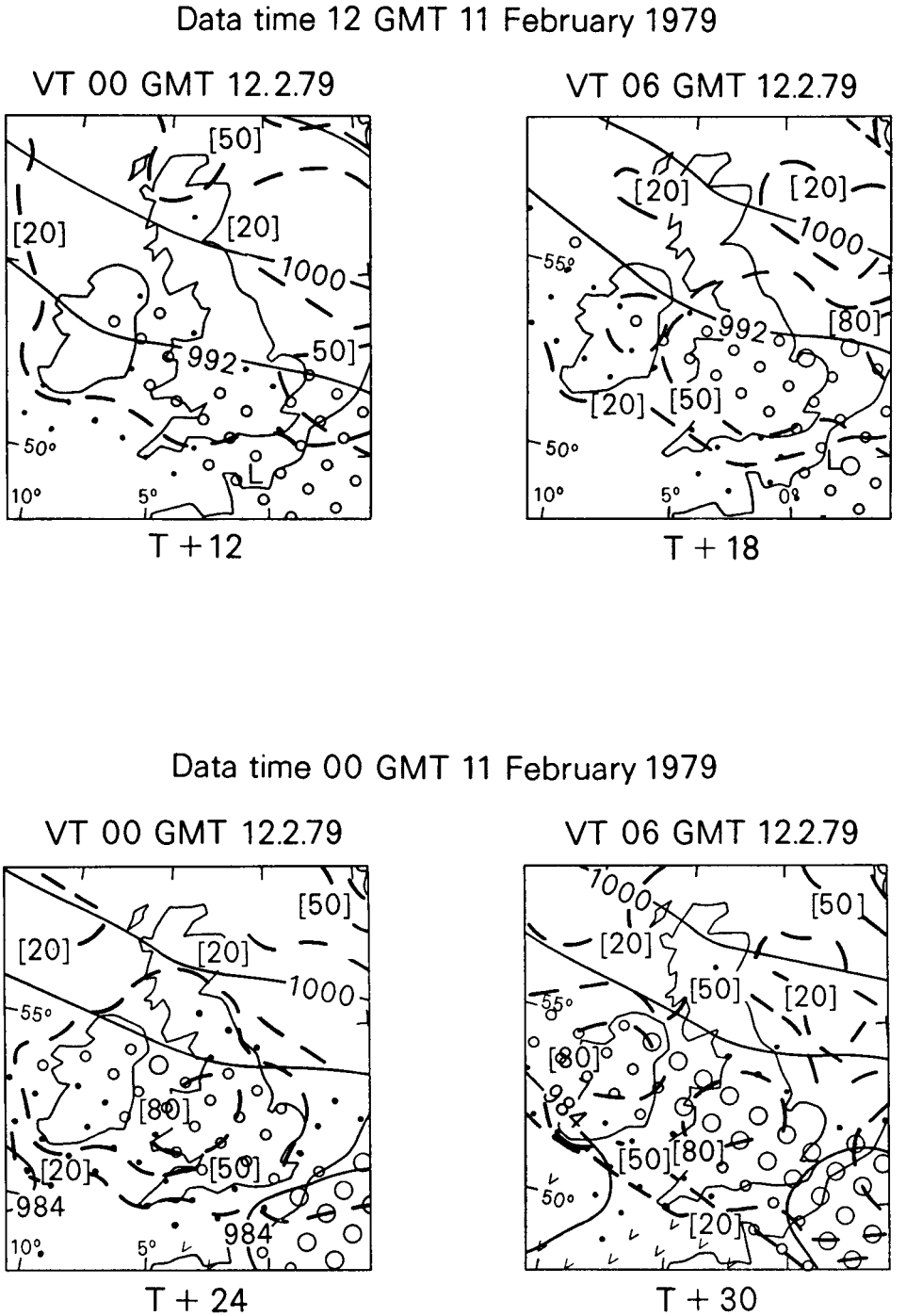
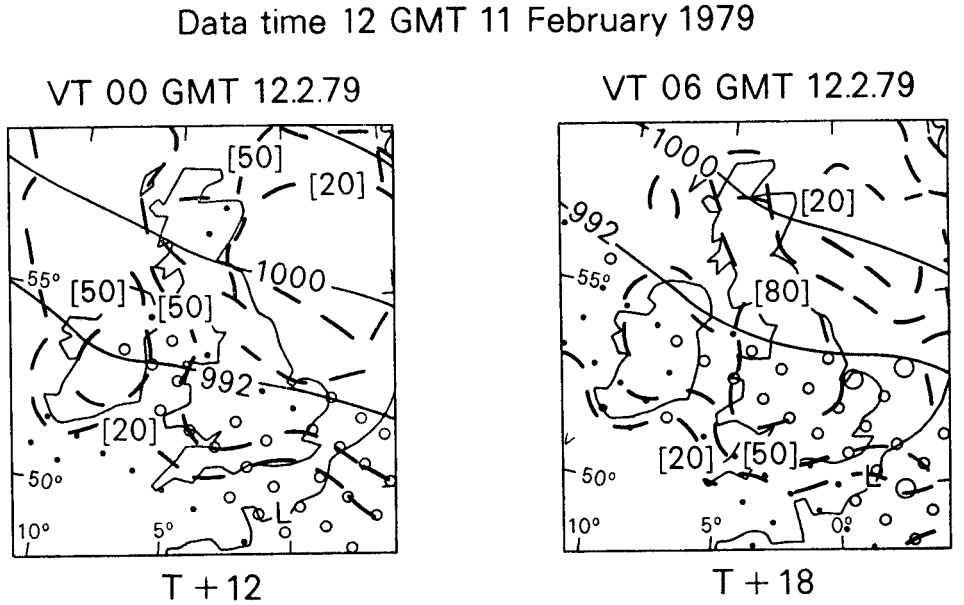


Figure 5(a). Forecasts produced using probabilities of snow corrected for sea-level pressure. Symbols and pecked lines as in Figure 1.



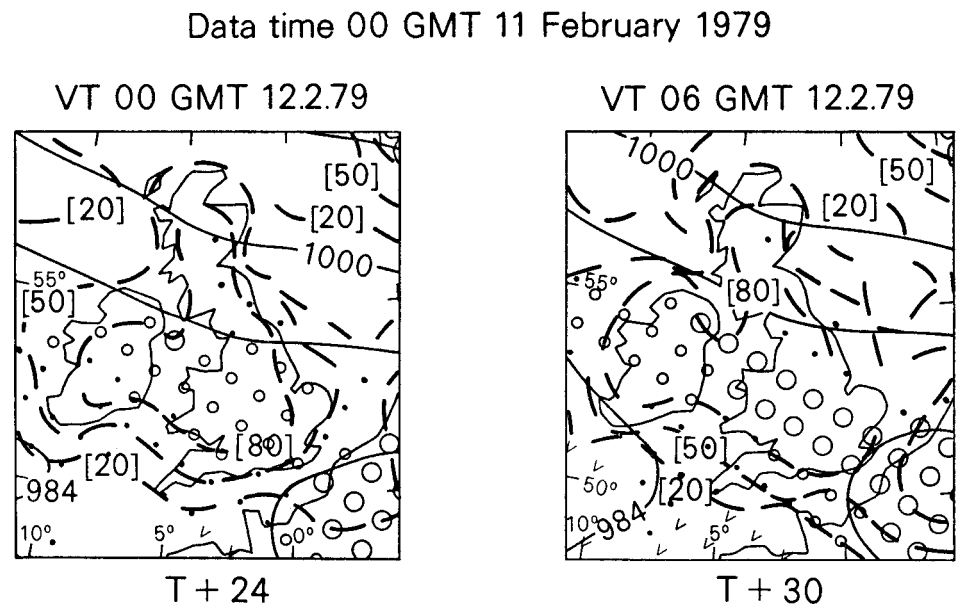


Figure 5(b). Forecasts produced using probabilities of snow corrected for sea-level pressure and topographic height. Symbols and pecked lines as in Figure 1.

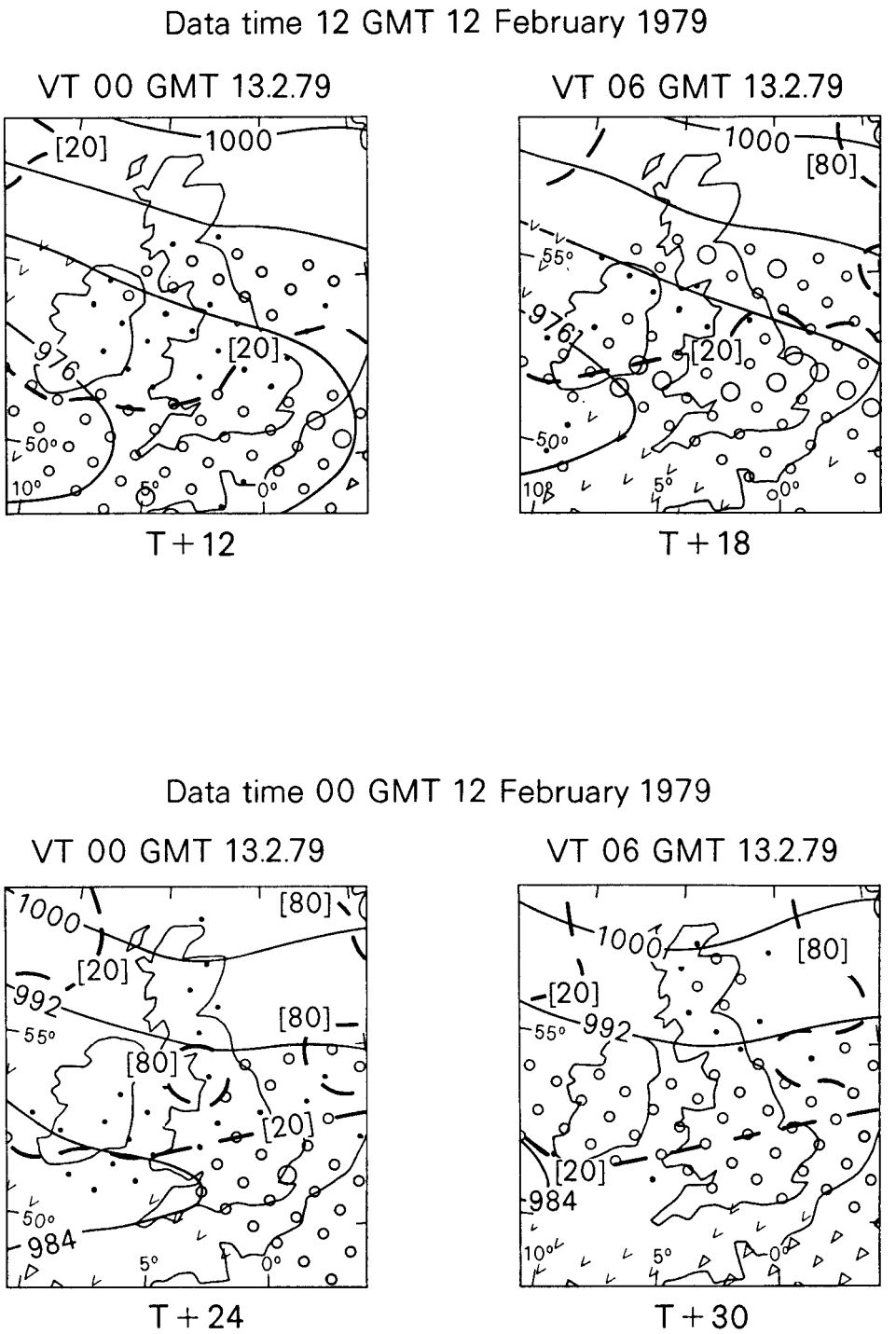


Figure 6. Operationally produced forecasts for 13 February 1979. Symbols as in Figure 1. Pecked lines as in Figure 4.

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551.5:358:92

Memoirs of an Army Meteorologist

By H. Cotton, M.B.E., D.Sc.

Part 5

[Dr Cotton described the battle of Passchendaele which took place in late summer and autumn of 1917.]

The assessment of any great event should be made, not on the short term, but on its long-term consequences. In the following spring the Germans launched two offensives which were intended to end the war in their favour. The first was the drive towards Amiens to separate the British from the French. The second was to reach the Channel coast and thereby isolate the British Army from England. Both came within a short distance of success, and both failed for the same reason, shortage of men. The reserves who would have turned the scale in Germany's favour were buried in the mud of Passchendaele.

With the end of the fighting and the advent of winter the British troops near the coast were withdrawn and the extreme left wing of the Allied armies again occupied by the Belgians. Apart from the fighting in the initial stages of the war, this Belgian sector had been very quiet; in fact, aerial photographs showed the tracks made by pedestrians leading from the Belgian to the German positions. There had clearly been much fraternization. When the British took over this fraternization came to a sudden end.

A seaside place, so attractive in summer, becomes less inviting when the weather is cold and wet and the days short. Meteor left along with the rest of the Fourth Army Headquarters Staff and I went to Meteor G.H.Q. which had moved from Hesdin to Montreuil. Montreuil is a walled town of great historical interest. It stands very high and the encircling wall is complete, a walk round it being a pleasant experience and affording magnificent views of the countryside. It was known to Henry V, Shakespeare's King Hal, 'with Agincourt for glory and the stake for zeal', who passed through it on the way to Paris. He passed through it again but in the opposite direction, a corpse on the way to burial in England.

The work at Meteor G.H.Q. was very similar to that at any forecasting establishment, even in peace time. There was the difference that a hopelessly wrong forecast, and a military operation based on it, might have disastrous results. As far as I remember there was no forecast so far out that it led to serious consequences. The chief task of the day was the preparation of the synoptic chart for the fundamental time of 7 a.m. since the forecast was based on this. This chart, along with the current situations at the various observer stations, was taken to the Colonel as soon as it was prepared. He then made his forecast and the chart, weather particulars from the forward stations and the current forecast were drawn in copying ink on a general weather chart. Copies were then made on a jellygraph—modern copying machines were not then invented—and these were distributed to the various headquarters at G.H.Q. Early in the forenoon the Colonel visited the Commander in Chief and discussed with him the

weather prospects for the day. Reports from local stations arrived throughout the day and at 6 p.m. the data for a new synoptic chart were received and the process repeated except that a general weather chart was not prepared. I appreciated the very great importance of the work at G.H.Q. but somehow I missed the excitement of the nearness to the fighting lines, particularly at the single observer stations like Le Touret.

Early in the new year of 1918 I was commissioned 'in the field' and became a Second Lieutenant, R.E. As far as the work at Meteor was concerned it made very little difference. A great change was the officers' mess which was managed on the lines of a good hotel. The waitresses all belonged to the W.A.A.C. and ours, at the Meteor table, was a very pretty girl named Edith. I never knew her other name. The food was a far cry from bully-beef and dog biscuit stew or, when things were bad, just dog biscuits without the bully-beef or the stew. The disadvantage of being commissioned was, from my point of view, the almost continuous saluting for it now included all non-commissioned ranks as well as the commissioned ranks from major upwards. Also, as it was G.H.Q. the powers that be were very snooty over such things. Occasionally I would visit one of the forward stations, to take a new member of Meteor or sometimes a replacement for a man who was going on leave. As the journey was made by G.H.Q. car I looked forward to such jaunts since it was a good way to see the country. It was amusing to see everybody stiffen up when they noticed the blue and red flash of G.H.Q. and I am sure that there were many unkind thoughts when men of much higher rank than mine realized that they had saluted a mere second lieutenant.

About the middle of February I went to Third Army Headquarters at Albert as a Meteorological Officer, and I felt that I was getting back into the heart of things. I looked at the famous hanging madonna and wondered about the legend. The Meteor office was in a very pleasant house some distance from the town on the Bapaume road. One day, walking along the road I came across the wayside grave of Colonel Wedgwood of the Fifth North Staffs. As I had met his wife previously I made a sketch of it and sent it to her. As the great German spring offensive against the Third and Fifth Armies started almost immediately after I posted it, it is possible that she never received it.

During the month of March 1918 the weather was established anticyclonic with light easterly winds, a clear sky both day and night and bitterly cold nights. A request was made for a gas attack on a troublesome sector of the Hindenburg defence system in the neighbourhood of the village of Noreuil. On the face of it such a request at a time of such meteorological conditions seemed sheer lunacy, but there were two factors which were favourable. The first was the new method of delivering the gas. The original method of releasing chlorine gas from cylinders was abandoned in favour of delivering the gas straight on the target by firing canisters of the gas from trench mortars. These did not explode but opened gently so that the gas was in the greatest possible concentration.

The second factor was the nature of the terrain. The Germans were masters in the design of defensive systems and all the way from the sea to the Swiss frontier they held the high ground. But in the neighbourhood of Noreuil there was a system of ridges and valleys, almost like the fingers of the hand, running in a roughly west–east direction. Even the Germans could not site their defences along contour lines in such a terrain and consequently they had to dip down into the valleys. This favoured the exploitation of a katabatic wind in the early hours of the morning, the best possible time for the maximum psychological effect of such an attack. Was this possible? It was the task of Meteor Third Army to find out.

The first thing was a request to Meteor G.H.Q. for a forecast covering as many days as possible and, because of the great stability of the anticyclonic system and no sign of its being displaced by a cyclonic system we were assured of stable conditions for, at least, several days. Continuous observations for two whole days and nights were therefore made of the winds in these valleys and it was found that the

gradient wind ceased well before midnight and then there was a gradual build up of the katabatic wind reaching about three miles an hour, an ideal velocity for such an attack, at about 3 a.m. The go-ahead for the attack was then given and in the early morning hours tons of pure phosgene gas were delivered from trench mortars. Phosgene gas, besides being a deadly poison, is extremely heavy and therefore, when gently released from the canisters, instead of a violent dispersal, it poured almost like a liquid into the trenches and dug-outs. I do not know whether gas masks offered any protection against this gas provided there was air to breathe, but there *was* no air to breathe. The phosgene in sinking simply displaced the air so that the gas masks, however efficacious, were useless. The casualties were very heavy.

It was a foul way to kill fellow human beings but the Germans started it. An atrocious weapon is only justified if by its use the war will be almost immediately ended. If it is not, then the other side will develop something even more atrocious, and so the Germans paid heavily for using gas in the first place. Without the co-operation of the meteorological services, both at Army Headquarters and at G.H.Q., this gas attack would not have been possible. It was the last gas attack of the war, but gas shells fired from guns were used right up to the end of the war.

The Germans used phosgene gas in the later stages of the Verdun battles and they believed that, at last, they would achieve a breakthrough and capture Verdun. They were so confident that they actually brought up military bands to head the triumphant march into the town. The gas was delivered in shells by the artillery, not in canisters from trench mortars as in our case, although the effect was at first the same. Because of the element of surprise and of a defect in the fabric of the French gas masks, which were not impervious to the gas, an advance greater than any since the very beginning of the Verdun battles was made. After that the attack petered out for two reasons, the first being that the French troops were hurriedly equipped with masks which were impervious to the gas. The second was the nature of the terrain. Practically every square foot of land in the battle areas had been ploughed up time and time again by the artillery of both sides. The French had no chance to construct the German type *Stollen*; in fact it would have been impossible to do so, the best they could achieve being hastily dug trenches. Consequently the gas, although it settled in hollows, dispersed horizontally and was thereby considerably diluted. In the Hindenburg line the deep dug-outs, although an almost perfect protection against artillery, were death traps in the case of an attack with a heavy lethal gas like phosgene because there was no possibility of dilution by dispersion. The atmosphere in the dug-outs became one of phosgene, not air, and so gas masks, no matter how efficient, were useless. I was told that we used, along with the phosgene, canisters of a penetrating gas which made the men remove their masks. It would have made no difference to those in the deep dug-outs but would have been effective in the case of those nearer the surface.

[Dr Cotton then describes the German attack on the British Third and Fifth Armies which took place in March 1918.]

What happened to the Fifth Army affected the Third Army and therefore affected me. Without doubt the southern half of this Army would have been compelled to fall back, apart from what happened to the Fifth, for with a bombardment of that nature, combined with the erroneous troop dispositions and the inadequacy of the defences, a stand was quite impossible. In addition it was necessary for the right flank to keep pace with the retreating Fifth Army left flank. The whole Army therefore pivoted on its junction with the First Army to the north.

I doubt if anyone in the Third Army Headquarters went to sleep that night. There was a very thick fog before the barrage started at 5 o'clock and immediately after breakfast I set out to bring in the forward observers. The whole of the Meteor equipment and records were then loaded on to a lorry and we, along with the rest of the Headquarters Staff, became the precursors of a general retreat. As we

passed the basilica I looked up at the hanging Virgin. She was still in her precarious position but very soon after she was brought down. It looked as though the prophecy was about to be fulfilled but with a German instead of an Allied victory.

As we retreated, French people came to the doors of the houses to watch the British going the wrong way. It was distressing to see the looks of despair on their faces although, as it happened, the German advance was halted at Albert.

The new Third Army Headquarters was at two neighbouring villages, Beauquesne and Terramesnil. They were pleasant, the countryside was pleasant, the sky was blue and the wind warm, and there was a carpet of anemones in the woods. Almost immediately I had to go again to the kite balloon, this time for the duration of the war.

It was very soon realized that the same balloon could not be used in a dual role, for meteorological observations and for artillery spotting, the main reasons being that meteorological ascents had to be made at fundamental hours in order that they could be correlated with ground-level observations, also that they had to be made no matter what the weather was like provided it was not such as to endanger the balloon as, for example, very high winds. So ascents were made under conditions which grounded balloons engaged solely in artillery work, very low cloud cover for example, or almost nil visibility.

So when I arrived the balloon had already been taken out of the line to the village of Strazeele about four miles west of Bailleul. Like practically all the villages in north-east France it was drab; in fact, I had the impression there must be a reason for this universal drabness. Perhaps past history provides the answer. The land on either side of the Franco-Belgian border is not called the cockpit of Europe for nothing.

The balloon personnel were not those I had worked with before; the two officers were Lieutenant West and Lieutenant Donkin, always referred to as Dinkle, although I never knew why. He was a good balloon man but all he could think of was girls, and it was clear that he had already found the village decidedly frustrating. He was only nineteen.

A few days after my arrival I was making the 7 a.m. ascent with Dinkle in charge of the balloon. He was in a bad temper, possibly because I had ordered the batman to pour cold water on his head as the only means of wakening him. A particularly loud alarm clock held right against his ear produced no effect whatever apart from a slight shuffling. An alternative method was to tip him out of bed but he would have continued to sleep on the floor if left alone. So he took a poor view of my joke about 'let go the guys'.

On 19 April 1918 the Germans commenced the second of their spring offensives and I thought I must be a kind of Jonah, being followed around by German offensives everywhere I went. On the first day they attacked on a front of 11 miles, extending this to 24 miles the next day. As the Germans had shown at Verdun, kite balloons can move forward during an advance and thus act as the eyes of the artillery but during a retreat they have to be moved to safety as quickly as possible. Early on the 10th we began to evacuate Strazeele. This meant deflating the balloon and packing it up, loading everything on to lorries, including a large number of gas cylinders, not to mention a vast amount of smaller stuff. I had seen to the disposal of my instruments in the light tender and that was all I could do apart from trying not to be in anybody's way. When the cavalcade was about to move off I noticed Lieutenant West approaching me in a great hurry.

'Will you do something for me?' he said.

'Yes, of course, if I can.'

'Wing has just rung through to say that a ferry pilot has ditched a brand-new plane with a secret engine in a field next to the Lunatic Asylum east of Bailleul, right in the way of the German advance.

As we are the nearest to it they want it sabotaged. But I can't spare Dinkle as we must be out of here as soon as possible, so will you do it?'

'Good gracious,' I said, 'I haven't the foggiest idea how to sabotage anything, let alone an aeroplane. Besides, my O.C. wouldn't like my taking on a thing like this without his consent. I must ring Meteor.'

'You won't get through.'

We tried and he was right. Eventually I said that I would have a go. Apparently all I had to do was to pour petrol over everything and set it alight. It sounded too simple. The R.F.C. were supplied with P and M motor-bikes and sidecars, the bikes having 500 c.c. single-cylinder engines with the cylinder inclined so as to be parallel to the front member of the frame. I had never driven one but my batman was familiar with ours. So I told him to drive and I sat in the sidecar, and we stowed sufficient petrol in cans to set fire to the whole Air Force. Once again there were the pitiful streams of refugees burdened with as much of their belongings as they could take away. It was almost impossible to make any headway, and as I had no idea how fast our own army was retreating the delay caused considerable anxiety. When we reached Bailleul, the town seemed to be empty and it was being shelled, although not very heavily. It was hop-growing country and I noticed several fields almost filled with the tall poles.

We reached the field and there was the plane, and in the next field was the Asylum, a red-brick monstrosity.

'That's where we ought to be', my batman said and I was inclined to agree with him. Just before we started pouring petrol over the plane, I had an idea.

'How are we going to set it alight?' I said to the batman.

'Bloody hell,' he said, 'I never thought of that. We shall very likely go up with it.'

I thought of the long hop poles and sent him to bring one. I tied a bundle of rag at the thick end so that it would travel true when thrown as a spear. Then we poured the petrol over what I thought would be the most important parts—there was quite a lake of petrol under the plane and this would help. I then poured petrol over the rag, set fire to it, threw the makeshift torch at the plane and then threw myself face down. There was a terrific whoosh and a hot blast like the inferno. The plane would certainly be a write-off after that although, of course, I had no idea whether the secrets of the engine had been destroyed. When we reached Bailleul on the way back the town was being heavily shelled and as we were crossing the end of the *Grand' Place* a shell made a direct hit on the clock tower of the *mairie* and I saw the beautiful blue clock tumbling down.

We had made only 20 or 30 yards further on when the bike stopped. An examination showed that the float was punctured. '*Now* what do we do?' moaned my driver. I remembered an article I had read in the journal *Motor Cycling*. The writer had substituted a large cork for the punctured float. We were fortunate. A little further on there was a chemist's shop. The door was locked, of course a useless precaution since it was certain the Germans would soon capture the town and loot everything. We broke in by smashing one of the windows with our spare petrol tin and, while my batman was looking round for what he could scrounge, I looked for corks which I found in a many-drawered cabinet. I took several, of different sizes, and fortunately one of them was just right. The repair was facilitated by the fact that the carburettor was a top-feed AMAL. If it had been a bottom-feed B and B—these were the two makes in most common use in those days—the makeshift repair would have been more difficult. Strangely enough I had to make a similar repair to a Blackburn machine I bought soon after demobilization and the cork was still functioning as the float when I sold it.

It was dark when we reached the new camp. I forget the name of the village, which was very small. I found Lieutenant West and gave him an account of all that we had done, and told him that if he didn't recommend me for the V.C. he ought to be shot at dawn. As it was, I thought it best not to court trouble by informing G.H.Q. so I heard nothing more about it.

The balloon was reinflated and the routine of three ascents a day was restarted as though nothing had happened.

The aim of this second German push was to reach the coast and thereby end the war 'at a stroke'. Fortunately they failed once again and their bolt was shot for good. I heard that they had overrun Le Touret, and that is as far as they got in that sector.

(To be continued)

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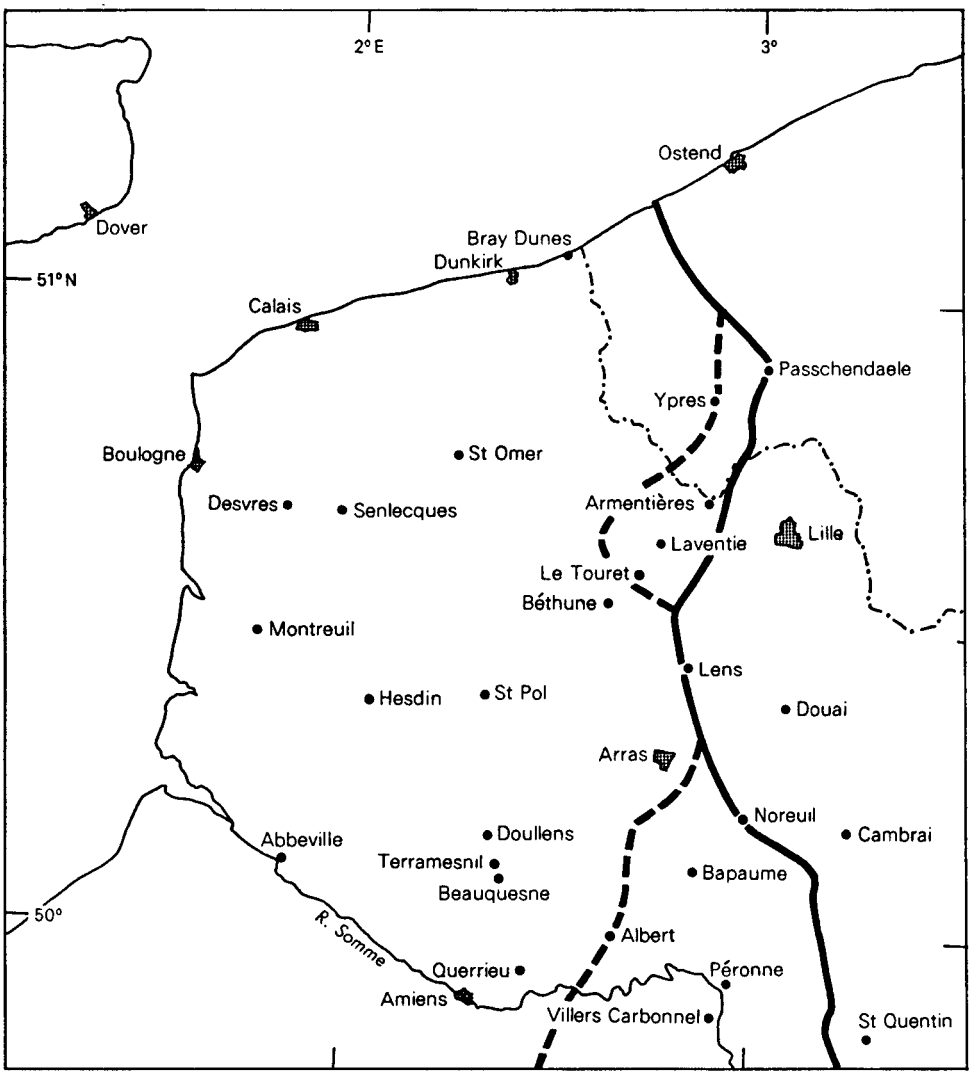

Map showing towns in Flanders and the Pas de Calais together with villages mentioned by Dr Cotton. The solid black line shows the rough position of the front line at the beginning of 1918, and the dashed line the extreme position reached by the German advance in the spring of that year. The Franco-Belgian frontier is also indicated.

551.5:06

Visit of His Royal Highness the Prince of Wales to the Meteorological Office, 15 June 1979

On the morning of 15 June 1979 His Royal Highness the Prince of Wales made an informal visit to the Meteorological Office. On arrival His Royal Highness was greeted by the Lord Lieutenant of Berkshire, Lieutenant Colonel the Honourable G. W. N. Palmer, who presented Sir John Mason, the Director-General. Sir John presented to His Royal Highness Dr K. H. Stewart, the Director of Research, Mr F. H. Bushby, the Director of Services, and members of the Senior Directorate.

Sir John conducted His Royal Highness to the Central Forecasting Office (CFO) where Mr D. E. Jones, the Assistant Director in charge, explained the work of CFO and presented several members of the staff who explained their work to His Royal Highness.

His Royal Highness also visited the COSMOS Computing Installation where the Director-General presented Mr W. R. Brady, the Computer Manager, who described the Installation and the work performed.

On his departure from the Office, His Royal Highness signed a specially illuminated page of the Visitors' Book. (See Plates I and II.)

551.5:06

The official opening ceremony of the European Centre for Medium Range Weather Forecasts

The official opening ceremony of the permanent Headquarters buildings of the European Centre for Medium Range Weather Forecasts took place on 15 June 1979. The opening ceremony was performed by His Royal Highness the Prince of Wales.

Following his visit to the Meteorological Office in Bracknell on the morning of 15 June 1979, His Royal Highness the Prince of Wales arrived at the European Centre for Medium Range Weather Forecasts in Shinfield Park at 11.20 a.m. He was accompanied by the Lord Lieutenant of Berkshire (Lieutenant Colonel the Honourable G. W. N. Palmer), Chief Inspector J. Maclean, and his Assistant Private Secretary (Mr O. Everett). The President of the Council of the European Centre for Medium Range Weather Forecasts (Professor L. A. Vuorela), the Vice-President of the Council (Mr R. Mittner), and the Director of the Centre (Dr A. C. Wiin-Nielsen) were presented to His Royal Highness.

The President of the Council conducted His Royal Highness to the reception area in the Centre and invited His Royal Highness to unveil the plaque commemorating the visit. The wording on the plaque read:

'This building was opened by H.R.H. the Prince of Wales, K.G., K.T., P.C., G.C.B., and presented on behalf of Her Majesty's Government to the President of the Council, Prof. L. A. Vuorela on behalf of the European Centre for Medium Range Weather Forecasts on 15th June 1979.'

After the unveiling, representatives of the Property Services Agency of the Department of the Environment and John Laing Construction Ltd, the building contractors, were presented to His Royal Highness. The Director of the Centre, accompanied by the President and Vice-President of the Council, then escorted His Royal Highness into the Computer Hall, where the party first visited the Meteorological Operations Room. The Director of the Centre gave a description of how medium range forecasts were to be produced operationally. Some of the Centre's current medium range forecasts were

then presented, including forecasts verifying on 15 June and predictions for the following week. The party then entered the Computer Room where His Royal Highness was given explanations of the functions of the various parts of the computer installation.

Upon completion of the tour, the party returned to the reception area, where His Royal Highness was invited to sign the Visitors' Book. After the signing the Director led His Royal Highness and the rest of the party to the marquee erected specially for the occasion in the grounds of the Meteorological Office College at Shinfield Park, immediately adjacent to the site of the Centre buildings. There, in front of the assembled staff of the Centre and the visitors, the Director of the Centre formally welcomed His Royal Highness. In reply His Royal Highness spoke of the complexity of the systems which went into the difficult task of weather forecasting, but emphasized the major economic and social advantages that were obtained by successful predictions. The President of the Council then thanked His Royal Highness for the presentation on behalf of Her Majesty's Government of the Centre buildings, and for formally opening them. In conclusion Professor Vuorela presented His Royal Highness, on behalf of the Centre, with a cut-glass decanter. A cheque for £1000 was also sent to the Prince's Trust.

Following the speeches in the marquee, the Director of the Centre escorted His Royal Highness and the rest of the party to the car park at the Centre. The Director of the Centre, the Vice-President of the Council and the Lord Lieutenant of the County took leave of His Royal Highness, who departed from the Centre at 12.30 p.m.

(See Plates III and IV.)

Reviews

The physical environment, by B. K. Ridley. 235 mm × 145 mm, pp. 236, *illus.* Ellis Horwood Ltd, Publishers, Chichester, 1979. Price £8·50.

This book, according to the author's preface, is intended to 'appeal to students of science and engineering, whether physical, biological, or social', and is based on a course for first-year science and engineering undergraduates at the University of Essex. This defines the standard of difficulty and depth of treatment of the text which provides a broad survey of astronomy, geophysics and meteorology; the topics dealt with include tidal friction, seismic waves, earthquakes, continental drift, natural forces and their manifestations from the atomic nucleus to tornadoes and the gulf stream, atmospheric radiation, and the origins of the universe and of life. It is obviously not a book written for the professional meteorologist, or the professional expert in any of the various disciplines treated, but is to be judged by how well it succeeds as a book of relatively advanced 'general science'. In general plan, and in basic quality of discussion and treatment, it is indeed a good and interesting book with many excellent plates and diagrams both in colour and in monochrome (some as fold-outs), 'optional' mathematical discussions set in small type, and useful bibliographies for 'further reading' at the end of each chapter. The text would, however, have benefited greatly from a thorough revision before being printed when a number of stylistic and grammatical slips might have been picked up; for example, 'a phenomena', 'pertain' for 'obtain', 'perform an average', 'continually' for 'continuously', 'emulate' for 'paraphrase', and, in particular, the section on the gulf stream where 'southern', 'southwards', 'south' and 'southerly' follow in quick succession in a confused piece of prose which would baffle anyone in an attempt to understand in just which directions the wind was blowing and the water moving; the account of the thermal wind, too, starts in a most misleading way.

On matters of fact, it is not true to say that 'a variation by about 0·5 per cent in the amount of sunlight received by the earth has been observed this century'. Claims that such a variation had been observed were indeed made some decades ago, but it is now known that the uncertainties of observation were too large for the variation to be accepted as real. (Better data may be obtainable in the future from satellites.) The albedo of land is far from constant at 20 per cent (p. 84), and varies from 12 per cent (tropical rain-forest) to about 35 per cent (desert).

The standard of textual editing is deplorable. Misprints abound, and abbreviations of unit symbols break—at random—all the rules of the SI system. On p. 151 the universal constant 3·14159 . . . is represented by Π, not π; Mohorovičić has lost his diacritics; in Figure 7.12, the diagram clearly shows an italic *l* as a subscript indicating the component of velocity along the pressure gradient, but the mathematical equations have a curious symbol resembling a rotated script 'e'.

The problems at the end of the book contain some oddities. The first (on Olbers' paradox) is really statistical, and the solution given—which assumes that all the opaque spheres contained in a volume of radius *R* are uniformly distributed over the surface of that volume—can only be a probability one. In problem 7.20, it should perhaps be made clear that the weather maps reprinted from *The Times* are forecast ones, not actuals.

A pleasant feature is the selections of prose and poetry after the chapter headings; they are obviously culled from a wide range of reading—much wider than dictionaries of quotations! The author's own style, however, is often too heavily jocular for the present reviewer, as when we are told of the 'maniac' observer at the centre of a rotating frame of reference, and of the 'fooling about' of the stars and sun.

To sum up: a book excellent in conception and general plan, but marred by lack of revision and by bad editing.

R. P. W. Lewis

Turbulent shear flows I. Selected papers from the First International Symposium on Turbulent Shear Flows, The Pennsylvania State University, University Park, Pennsylvania, U.S.A., edited by F. Durst, B. E. Launder, F. W. Schmidt and J. H. Whitelaw. 245 mm × 165 mm, pp. viii + 415, *illus.* Springer-Verlag, Berlin, Heidelberg, New York, 1979. Price DM 98, US$53.90.

Turbulent shear flows I contains selected papers from the First International Symposium of that name grouped under five section headings, namely Free Flows, Wall Flows, Recirculating Flows, Developments in Reynolds Stress Closures, and New Directions in Modelling. The editors must be commended on their careful selection of material, which has produced a very readable and clear account of research presented at the Symposium. The printing and the reproduction of diagrams are also of a uniformly high standard. It must be pointed out that most of the papers, in fact all of the first three sections, are concerned with flows from engineering situations. The section on Reynolds Stress Closures contains the only three papers directly concerned with meteorological flows; these papers discuss the effects of buoyancy in the planetary boundary layer. However, the rest of the book, especially the last section which has an emphasis on subgrid modelling, contains many fundamental papers of interest to anyone studying the dynamics of turbulent shear flows. On the whole, I think that the high quality of production and the careful editing of material definitely justifies the slight delay in publication of these conference proceedings.

R. I. Sykes

Award

We note with great pleasure that the twenty-fourth International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded to Professor Helmut Erich Landsberg (United States of America).

Professor Landsberg has established himself as one of the world's leading figures in climatology and associated disciplines. He was one of the first to realize that climatology would need to be given a much higher priority by those responsible for dealing with world affairs—a challenge which WMO is now meeting by the recently approved World Climate Program.

Notes and News

'Earth' and 'soil' temperatures

For many years the Meteorological Office has described temperatures measured below ground level as 'earth' or 'soil' temperatures according to the depth of the measurements. It has now been decided that all such measurements will in future be referred to as 'soil' temperatures, in conformity with a recent World Meteorological Organization recommendation.

Enhancement of the Meteorological Office computer system

An order has been placed by the Central Computer Agency with Control Data Limited, the U.K. subsidiary of the large U.S. computer company Control Data Corporation, for the supply to the Meteorological Office of a CYBER 203E computing system. This computer is an enhanced version of their existing CYBER 203 machine. It is expected that it will meet, with a comfortable margin, the minimum requirement for ten times the power of the IBM 360/195 currently used at Bracknell, Berkshire. The new computer is planned to operate in conjunction with the existing IBM computers and is scheduled for installation early in 1981.

The CYBER 203E will enable the Meteorological Office to study the atmospheric processes which determine the global climate. The large variations in the general circulation of the atmosphere, which cause big differences in regional weather patterns from year to year, and the systematic changes in climate which might be inadvertently brought about by Man's activities, are of world-wide concern and this has led to the institution of a World Climate Program, supported by nearly all nations, beginning in 1980.

The global climate will be simulated numerically by an advanced computer model and the influence of relevant factors studied by observing the response of the model to variations in these. A better understanding of the mechanisms responsible for climate should improve long-range weather predictions and enable better judgements to be made on the likelihood of systematic changes.

The computer will also be used to develop methods for producing more detailed short-period forecasts for specific areas of the British Isles and will take over the routine production of forecasts for a few days ahead.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

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